BERMUDA AQUACULTURE SUITABILITY ANALYSIS

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Preparation of this document

This report is a qualitative evaluation of potential culture candidate species and marine areas to explore the suitability of aquaculture in Bermuda. It is intended to contribute to the Blue Economy Strategy and to the Marine Spatial Plan, both of which are developed through the Bermuda Ocean Prosperity Programme (BOPP, 2020-2021). BOPP is a partnership among the Government of Bermuda, the Waitt Institute, and the Bermuda Institute of Ocean Sciences (BIOS). The goal of BOPP is to foster the sustainable, profitable, and enjoyable use of ocean resources for present and future generations. This work is funded by the Waitt Institute, and the report is compiled by Dr. Samia Sarkis, based in Bermuda and specialised in aquaculture. At the time of writing, there is no existing aquaculture activity in Bermuda; experimental work was conducted on the turkey-wing mussel (PI: Dr. S. Sarkis, 1988-1992), on the dolphin fish, *Mahi mahi* (PI: Dr. T. Sleeter, 1990s), sea cucumber *Isostichopus badionotus* (PI: Dr. S. Sarkis, 2014), scallop (PI: Dr. S. Manuel, 2001), and a pilot scale fully integrated scallop operation for native species, *Argopecten gibbus* and *Euvola ziczac* was developed (PI: Dr. S. Sarkis,1999-2003). There has been no further development of aquaculture in Bermuda attributed in part to lack of national priority, and lack of investment.

This report aims to identify and prioritise the most suitable aquaculture species and methodology (including at least 1 finfish species) to Bermuda, taking into account the species' biological and culture requirements, potential impacts, and projected yield. This is achieved by gathering Bermuda-based quantitative and qualitative data on natural stocks, water quality and other nearshore and offshore characteristics, primary data through interviews with experts, and secondary data on a range of aquaculture aspects (cultivation technology overseas, international guideline on Best Management Practice, environmental concerns, etc.) reported in the literature including peer-reviewed scientific papers, international relevant agencies publications (Food and Agriculture Organisation- FAO), and technical guides.

The main outputs of this document include a prioritised list of species, a summary of known farming techniques to market size, and the identification of suitable sites inshore and offshore Bermuda based on their physical carrying capacity. This provides a preliminary identification of marine aquaculture areas. Final site selection is beyond the scope of this report; recommendations are given for an in-depth assessment for suitability of commercial scale culture with associated impacts, and its validation through experimental/pilot scale assessments. The economic viability of an aquaculture operation requires a business plan and financial analysis also beyond the scope of this report. Finally, data presented here should be updated on a regular basis; species and technologies other than those prioritised and compiled in this document may prove worthy of consideration with advancing research and technology, and should not be excluded in future proposed ventures.

This document is intended for policy and decision-makers, as a guide for developing aquaculture in Bermuda, and includes environmental and regulatory considerations. In order to develop a sustainable aquaculture sector, a well-defined strategy for profitability and expansion is needed.

GIS maps with surface area and depth characteristics for sites were prepared by Sarah Brooks and Matt Paufve (The Waitt Institute). All physical and chemical seawater characteristics were obtained from scientific monitoring by the Bermuda Institute of Ocean Sciences and the Department of Environment and Natural Resources (Government of Bermuda). Production statistics if not noted, are from Food and Agriculture Organisation (FAO) records.

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Executive Summary

The objectives of this report are to prioritise species suitable for aquaculture in Bermuda, and to delineate areas of potential for mariculture development by identifying the spatial extent viable for growth of current and emerging species in inshore and offshore waters. There is no precedence for commercial aquaculture in Bermuda; but previous experimental (DENR, Government of Bermuda) and pilot scale operations (Bermuda Institute of Ocean Sciences) give a first insight into the potential and challenges of mollusc and finfish culture. Focus is on technologies utilizing a land-based hatchery (producing seed/juveniles) and an ocean-based farm (producing market size) for the development of a fully integrated marine aquaculture operation. Only species native to Bermuda are considered as potential culture candidates. Initial listing includes 17 native species with market demand and data on culture techniques; this includes both low trophic and high trophic level species – bivalves, echinoderms, gastropods, seaweed, crustacean and finfish. Listed species are prioritised from level 1-3 (1 being the highest), based on their suitability and readiness for commercial scale culture application in Bermuda.

Priority Level 1 consists of 6 culture candidates- 3 bivalves and 2 finfish- . Criteria for selection are culture knowledge and performance (hatchery and farm), source of stock, market demand, availability of suitable areas, potential production yield, and potential impact to the environment. Key attributes of Level 1 species are summarised in Table 1.

Table 1. Prioritised (Level 1) mariculture candidate species for Bermuda, 2021.

Species	**Farm culture system (juvenile to market-inshore/offshore)**	**Source of stock-local or import**	**Product type/market size or weight**	**Time to market (egg to market)**	**Harvest volume**
Calico scallop, *A. gibbus*	Sub-surface nets on longlines.	Broodstock- local or import	Whole fresh/ 55mm	18-24 months	18,000 scallops/100m longline
Lion's Paw scallop, *N. nodosus*	Sub-surface nets on longlines.	Broodstock- import	1. Whole fresh/120mm 2. Shucked muscle/ 30-60g (10-30, U12 meat count)	16-24 months	4,800 scallops /100m longline 144kg meat/100m longline
Pearl oyster, *P. imbricata*	Sub-surface nets on longlines	Broodstock- local	1. Pearl 2. Meat weight (20g/oyster)	18-36 months	1,000oysters/ 100mlongline 50-500 pearls/100m longline
Lane snapper*, L. synagris*	Submerged offshore cage culture	1.Fertilised eggs-import 2. Broodstock-local	Various: whole, fillets, fresh, frozen/ 1kg market weight	12 months	7,200 fish/300m^3 cage (7.2mt/**300**m^3 cage)
Almaco jack, S. *rivoliana*	Submerged offshore cage culture	1.Fertilised eggs-import 2. Broodstock-local	Various as above. Sashimi/ 3kg market weight	16 months	15,000-20,000 fish/3000m^3 cage (45-60 mt/**3000**m^3)

Relevant criterium for hatchery site selection is access to high quality seawater. Farm sites are identified with respect to physical carrying capacity, using the following environmental layers: Depth, temperature, salinity, turbidity, residence time, dissolved oxygen for shellfish and finfish; additional layer for bivalves is natural food availability (chl a), and for offshore finfish are distance to shore, distance to reef, and current speed, as these place technical constraints on the infrastructure. Five inshore sites are identified for bivalves, and 11 offshore sites for finfish. Environmental concerns, constraints and risks are discussed for each priority Level 1 species; higher trophic level finfish species have a higher negative impact than lower trophic level bivalves; alternatives to offshore cage culture is discussed. Best Management Practice for reduction of risks and negative impacts are considered. The following recommendations are made to determine type and scale of production, and scope for expansion: Follow up on identified sites in this study with individual localized and detailed investigations; assess site-specific ecological, production and social carrying capacity; validate technology and carrying capacity through site-specific pilot scale or 'demonstration' projects; investigate possibility of combining aquaculture of species in priority levels 1, 2 and 3, belonging to different trophic levels (Integrated Multi-trophic Aquaculture) (IMTA); investigate possibility of combining farming technology with other industry sectors. The need for a multi-annual aquaculture plan, based on an ecosystem approach strategy and supported by policy and regulatory mechanisms for developing a sustainable aquaculture sector in Bermuda, is emphasized.

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1. Introduction

There is no precedence for commercial aquaculture in Bermuda; experimental and pilot scale operations have been conducted on finfish, bivalves and holothurids (sea cucumbers). Developing an aquaculture industry in Bermuda was first discussed in 1983 during an international workshop with Caribbean and U.S. experts at the Bermuda Institute of Ocean Sciences (Sleeter, 1984).

The objectives of this report are to prioritise species suitable for aquaculture in Bermuda, and to delineate areas of potential for mariculture development by identifying the spatial extent viable for growth of current and emerging species in inshore and offshore waters.

Bermuda, a 55 km^2 land mass in the middle of the Atlantic Ocean (32°N, 64°W), supporting a resident population of 62,000, is densely populated (1,145 people/km^2); the island's two main industries are international business and tourism. Food security is a concern as 90% of all food imported. Since 1990, commercial fishing production averages 400 metric tonnes (FAO, 2018), and does not satisfy the estimated 45kg fish and seafood consumption per capita (2013).

Although included in the Wider Caribbean Region (FAO), Bermuda lies over 1,200 km to the north of its nearest Caribbean neighbour (the Bahamas), with the closest continental point of land being Cape Hatteras, North Carolina, 965 km to the west. Bermuda has a sub-tropical climate, supporting the most northerly coral reef ecosystem in the Atlantic, with a fauna and flora composed of similar species to those found in more Southern Caribbean islands. Seawater ambient temperatures show marked seasonal variations in the inshore waters, and minimal temperatures are close to the lower tolerance limit for many species. This in turn affects the reproductive cycle and growth rate of marine species. Of direct impact to aquaculture, distinct spawning periods are known for a number of species, and restricts the scope of seed/juvenile production in a hatchery environment; growth rates are comparatively lower than those reported in tropical regions.

Bermuda lies on the southern rim of the largest of three steep-sided sea mounts (Fig. 1). To the southwest lie Argus and Challenger Banks seamounts; these are characterized by platforms at 50m depth increasing to 70m, where a sharp change in depth occurs to the steepening slopes of the underlying seamount (Coates *et al.,* 2013).

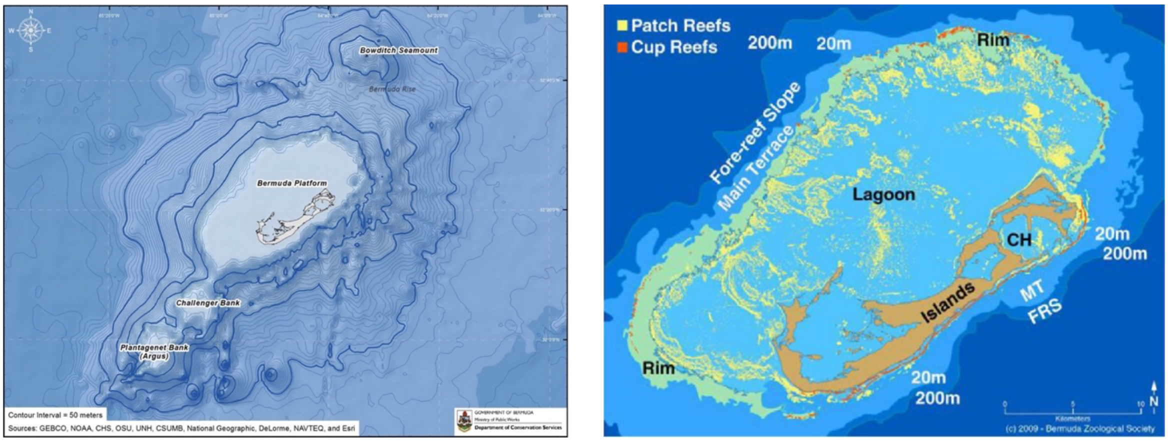

Figure 1. Bathymetry of the Bermuda Pedestal and nearby seamounts (left); Bermuda map showing lagoon and reef contours with depth (right).

The shallow-water Bermuda platform extends seawards and includes: The lagoonal reefs comprising patch reefs (15m average depth), rim reefs (2m-15m), terrace reefs (10-20m), sloping at <10° to the fore-reef (20-50m) (Fig. 1). Beyond which, a steeper slope commences with depth increasing rapidly to almost vertical walls of 100 m. On the south shore of Bermuda lie the 'boiler' reefs 1.5 km from shore, beyond which depths increase rapidly from 20m-200m.

Bermuda's marine ecosystem is considered relatively healthy, and supports one of the most pristine reef systems of the Wider Caribbean. Successful aquaculture development can only be sustained if the environment is favourable to a species' culture requirements, and conversely, aquaculture activities should not have a long-term negative impact on the environment. With the exception of known point sources of pollution, seawater quality is good in Bermuda and conducive to the culture of early life stages (larvae/post-larvae) and juveniles. The proximity to a heavily populated landmass and activities driven by economic growth is a risk factor in the sustainability of the marine ecosystem. In order to reduce or eliminate the added risk brought about by the development of an aquaculture sector, an ecosystem-based[1] approach is recommended. Achieving this requires a tight coupling of science, policy and management. Bermuda's approach to developing aquaculture can be expressed as:

- Increase social and economic impact through the production of food, contribution to livelihoods and generation of income.
- Contribute to provision of seed for restocking endangered or overexploited populations
- Enable good management to ensure that ecosystems functions and services are retained
- Protect aquaculture from other human activities, such as contamination of water

Aquaculture systems differ widely dependent on species, scale of production, environmental conditions, available infrastructure, coastal usage, bathymetry, budget, etc. Candidate species for aquaculture can be divided into two broad categories, a) low trophic, and b) high trophic. In the aquaculture sector, the trophic level of a cultured species is directly proportional to the required input (feed) of the farming activity. Briefly, species with a high trophic level (such as marine carnivorous finfish) require a high daily amount of externally provided protein-rich feed. This results in environmental impacts on the source of food, and on the waste products generated by the cultured species into the natural environment. On the other hand, low trophic species (such as bivalves) require no external feed input, as they derive their nutrients from the water, and in some cases positively impact on water quality (Tacon *et al.*, 2010). Finfish aquaculture is an important source of protein for humans, and research worldwide is focused on improving technology to reduce negative impacts of large scale mariculture operations on the environment.

There are several naturally occurring marine species in Bermuda with known and tested culture techniques at the experimental, pilot or commercial scale. This report provides a first list based on the available data in culture know-how, and potential market (Appendix 1). The list is subsequently prioritised into 3 levels based on criteria described in the relevant sections; cultivation technology, environmental concerns and best management practices are discussed for top species (Level 1). Suitable sites for Level 1 species are mapped and reflect the physical carrying capacity of the site, based on identified environmental layers. Alternative culture methodologies and R&D requirements are given for lower priority species (Levels 2 & 3). Economic and technical constraints, and risks most relevant to Bermuda are identified. Recommendations address the approach to final species-specific site selection and the validation of proposed technology and associated environmental impacts through pilot scale/demonstration projects for relevant species. The report concludes with the need for regulatory mechanisms supporting the development of the aquaculture sector, new to Bermuda.

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[1] An ecosystem approach to aquaculture (EAA) is defined by the Food and Agriculture Organisation (FAO, UN) as 'a strategy for the integration of the activity within the wider ecosystem, such that it promotes sustainable development, equity and resilience of interlinked social-ecological systems'.

2. Prioritised Culture Species for Bermuda

The success of an aquaculture venture is primarily determined by its ability to operate a profitable business in an environmentally, economic and socially sustainable manner. Culture techniques for the top species (Level 1) prioritised in this document are well tested at the pilot and commercial scale in Bermuda or elsewhere; they can be implemented with relatively few adaptations to specific sites in Bermuda's waters.

A fully integrated aquaculture operation consists of:

- A land-based broodstock area – for a source of eggs as start-up of the culture cycle
- A land-based hatchery – for production of seed/fingerlings
- An intermediate nursery (land/pond/coastal water based)– for growth of seed/fingerlings to size adequate for transfer to farm
- A nearshore or offshore farm – for grow-out of juveniles to market size
- A processing/packing/shipping plant (dependent on market product form and market location)

Note: An aquaculture operation can include all or some of the components above.

Key requirements for the land-based hatchery with respect to spatial planning are:

- Incoming source of clean seawater,
- Access to farm sites, and
- A coastal area for intermediate nursery facilities.

Final site selection for the nearshore or offshore farm is critical to the success of the aquaculture venture, and depends on the carrying capacity of the site and its ability to support the projected stock of cultured animals. A description of carrying capacity is given below.

2.1 Carrying capacity

This document informs the physical carrying capacity and to some extent the production carrying capacity for mariculture farm operations in Bermuda. Full carrying capacity includes:

<u>Physical carrying capacity</u>- identifies sites or potential aquaculture zones from which a subsequent more specific site selection can be made for actual development. It takes into account the physical factors of the environment only.

<u>Production carrying capacity</u>- estimates maximum aquaculture production and is dependent on the technology, production system, and investment required; this is based on the stocking density at which harvests are maximised.

<u>Ecological carrying capacity</u>- defines the magnitude of aquaculture production that can be supported without leading to significant changes to ecological processes, services, species, populations or communities in the environment.

<u>Social carrying capacity</u>- represents the amount of aquaculture that can be developed without adverse social impacts. (Ross *et al.,* 2013)

2.2 Farm Site Selection Considerations

A farm is the cultivation area for grow-out of juveniles to market size, and is selected based primarily on it suitability to species specific aquaculture production. Comprehensive check lists are available in the literature for a thorough assessment of site suitability The choice of a farm site affects:

- Production scale

- Impact of the farm on the environment
- Impact of the environment on the aquaculture operation

2.3 Criteria species selection

Species deemed suitable for aquaculture in Bermuda are selected based on:

- Native status of species to Bermuda
- Known culture techniques for the whole life cycle, or part of the life cycle.
- Growth and survival rate under cultured conditions,
- Access to seed/fingerling supply,
- Market demand,
- Availability of suitable areas in Bermuda,
- Potential production yield, and
- Level of potential impact to the environment.

Levels of prioritisation are given for species (levels 1-3). This report calls for the prioritization of 2-3 species, including one finfish species, and a first assessment of suitable farm sites for the allocation of aquaculture zones in Bermuda's Marine Spatial Plan. For this reason, Level 1 species include those with an ocean-based farm component.

Level 1:

- Species with ready to go or nearly ready to go technologies
- Species requiring nearshore or offshore sites for juvenile to market farming

Level 2:

- Species cultured to market size using land-based technologies only

Level 3:

- Species with recognised challenges during at least one phase of their life cycle
- Slow growing species
- Small market and/or
- Species which require a comprehensive R&D phase to establish culture protocols

3. Priority Level I

3.1 Bivalves (Low Trophic): Culture, market and production

Marine bivalve aquaculture is an extensive form of aquaculture, where bivalves feed on algae that occur naturally in the ecosystem. Production at the farm stage relies on the natural productivity of marine phytoplankton, in the form of living algae or detritus, transported to the bivalves by water flow- such as currents and tidal exchange. There is no input of nutrients in the farm site; the only input of nutrient is during the hatchery stage in land-based tanks for the first 3 months of their life cycle. Marine bivalves are considered a sustainable type of food production (Wijsman *et al*., 2019).

Three bivalve species are suitable for Bermuda; two scallop species, and one oyster species. Scallops are discussed as one group, as similar techniques and equipment are applied.

3.1.1 Scallops: Calico scallop, *Argopecten gibbus*, and Lion's Paw, *Nodipecten nodosus*

Note: Live lion's paw scallops have not been reported in Bermuda, and records only indicate the collection of empty shells in deeper Bermuda waters. Approval for culturing this species depends on its native status classification by the Department of Environment and Natural Resources (Government of Bermuda). See Appendix 1for details of its distribution.

Culture techniques and source of seed:

The Bermuda-tested technology for pilot scale culture of calico scallops make these ideal, low risk candidates for a first aquaculture operation. Culture of the lion's paw is a well-known established technology from Brazil (Rupp and Parsons, 2016), and provides a strong information base for transfer of technology to Bermuda. The short larval life cycle for both species is advantageous as it increases the capacity of juvenile production within a given space through repeated spawning cycles per season.

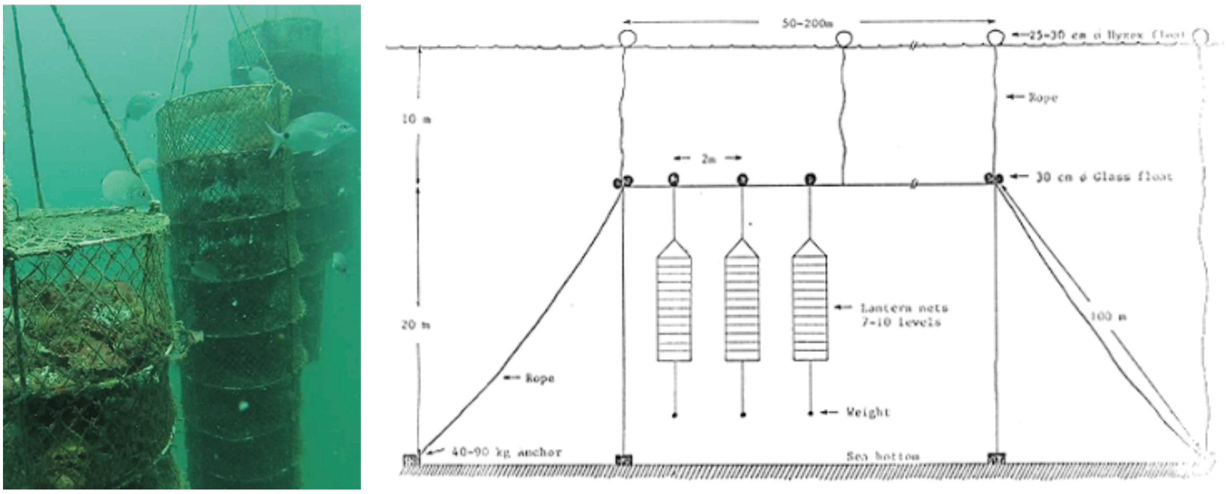

Figure 2. Left: Photo of lantern nets with lion's paw scallops in Brazil (G. Rupp). Right: Schematic of a longline with suspended nets on a submerged line, secured to the bottom with anchors, and marked at the surface with floats.

Both of these species are conducive to suspended cultures in the water column; this facilitates maintenance for labour and harvesting, and enables scaling up.

There are two main types of suspended cultures for scallops, both are secured as a longline system suspended in the water column by buoys, at the surface or submerged (Fig. 2):

a. Pearl and lantern nets provide protection from predators and yield high survival rates (Fig. 2). Traditionally used for several scallop species worldwide, both pearl nets – frequently used for young seed- and lantern nets have been tested for both calico and lion's paw scallop.

b. Earhanging is used widely in Japan for the large sized Japanese scallop, and pilot operations are conducted off the East Coast of the US for other species (Fig. 3). Earhanging requires the drilling of a hole in the scallop shell, and threading of scallops onto one line, which is thereafter clipped onto a longline. This can be done manually, but for efficiency and large scale, an automated earhanging machine is used. Labour required for fouling control and stocking density adjustments is lower than that required for nets. For Bermuda, this technology would be most relevant to the larger sized lion's paw scallop. Although animals have no protection against predators, there are few reports of loss of stock due to predation (D. Morse, *pers.comm.*).

Figure 3. Earhung scallops (Sea scallop, Placopecten magellanicus) in experimental trials in Maine (D. Morse)

Both scallop species reach market size within 24 months (from egg), with survival rates from juvenile to market size during the farm stage considered good, and averaging 90% (Sarkis and Lovatelli, 2007; Rupp and Parsons, 2016). Seed supply for calico scallops is not available overseas as there is no known commercial hatchery; lion's paw seed could potentially be obtained from Brazil. Seed production can be generated through a Bermuda-based hatchery, and broodstock may have to be imported dependent on levels of natural populations. Best management practices would apply to any imported organisms (Appendix V).

Market demand and product type:

Scallops are one of the most popular seafood items due to their unique appealing texture and succulent flavours. Scallops are sold mainly as whole or adductor muscle only (meats) only; in the US consumer preference is for the latter. Scallop muscles are sold by size categories, with large scallops yielding 10-30 meats/ pound, medium scallops 30 -70/pound, and small scallops 70- 110 per pound. Calico scallops are of relatively small market size (55mm), and yield a low meat count (150-200); the small muscle size for this species is a major factor in the lack of interest in its aquaculture development in the U.S.A. (Lovatelli and Sarkis, 2011). Lion's paw scallops have a substantial adductor muscle, weighing 30 to 60g, and yield one of the best meat counts averaging10-30 meats per pound, with largest animals yielding the highly prized U/12 meat count (10-12 meats per pound). The current domestic market demand for scallops is 100% supplied by import of meats. Bemuda acceptance of locally grown calico scallops was tested during the BIOS pilot scale programme (2003); the whole fresh product with roe ($1.00/scallop) received high chef and consumer acceptance (Fig. 4). This potentially satisfies part of the domestic market demand, currently 100% supplied by import of scallop meats. Producing both calico and lion's paw scallops expands the scope of end product. Tapping into the export market is dependent on production, processing and shipping costs, and a competitive market price. US market prices for sea scallops range from US $9-$12/pound (Shahbandeh, 2021), and current prices for lion's paw muscles in Brazil average $12-$15/dozen (Marquez *et al.,* 2018).

Figure 4. Bermuda grown calico scallop, A. gibbus, ready for market and showing roe (S. Sarkis)

Production yield:

Actual production yield will depend on environmental conditions- such as temperature and natural food availability. Complex bioenergetics models are used academically to assess species production yield and site suitability, such as the STELLA model (FARM Resource management for shellfish; Ferreira *et al.,* 2007).

Insight into production yield is given here based on the projected harvest per longline; this is based on stocking and harvest densities derived from previous culture data (Sarkis and Lovatelli, 2007; Rupp and Parson, 2016). It is a first step in estimating the maximum aquaculture production carrying capacity (see Section 2.1).

Table 2 summarises culture densities, and harvested product characteristics used to estimate the number and weight of scallops per 100 m longline; the distinction between both products- whole live scallops for both species, and shucked meat for the lion's paw - is made. This gives a rough estimate of potential production yield per 100 m longline. Fresh muscle weight for lion's paw is averaged at 30g.

Table 2. Estimated production yield and time to market (from eggs) for calico and lion's paw scallops in Bermuda.

Bivalve species	**Stocking density range (seed/juveniles)**	**Harvest density**	**Harvest size (mm)**	**Harvest meat weight (g)**	**No. of market size scallops/100m longline**	**Harvested Kg /100m longline**	**Time to market**
Calico scallop	100/layer	30/layer	55	3.5g	18,000	900 kg whole live wt/longline	18-24 months
Lion's paw scallop	100/layer	8/layer	110	25-55g	4,800*	7,200 kg whole live weight/longline 144 kg muscle weight/longline	16-24 months

*lower number of scallops per longline due to larger size of lion's paw adult and greater space requirement

3.1.2 Pearl oysters, *Pinctada imbricata*

Culture techniques and source of seed:

Hatchery culture techniques for oyster seed production follow closely those used for scallops, and similar facilities are used. The farming of pearl oysters is well known and tested elsewhere, although most operations rely on the collection of wild spat (young seed). *Pinctada imbricata fucata*, a closely related species to the Bermuda native *Pinctada imbricata radiata*, is cultured commercially in Australia using a fully integrated aquaculture operation (hatchery and farm); it produces Akoya pearls, the smallest of the three saltwater pearl categories (Otter *et al.,* 2017).

Pinctada imbricata is distinct in the range of colour seen in its nacre; this translates into the production of naturally coloured pearls from cream, pink, green to silver, and brings uniqueness to the product. *P. imbricata* is also consumed for its meat in the Caribbean (Lovatelli and Sarkis, 2011), and both meat and pearl products can be generated from the same operation. Pearl production is a two phase step, and requires the initial growth of 70 mm oysters, which are thereafter grafted and 'seeded' to stimulate pearl production. Pearl oysters in Bermuda are observed to be fast growing, and estimated to attain 70 mm in 12-18 months, based on the literature (Urban, 2000). Time to market includes a further 6-18 months for the formation of a full pearl; the longer the time period the thicker the nacre (Urban, 2000; Otter *et al.,* 2017). The oyster is sacrificed to remove the pearl, and pearls are buffed and graded according to colour, luster, shape and size. Gem quality can be achieved for up to 50% of the pearls produced, with pearl size from 6.5 to 8 mm (Otter *et al.,* 2017).

Farming oyster seed to market size is conducted using a range of technologies (Fig. 5). The two most relevant technologies to Bermuda are similar to those for scallops and are: 1) trays or panel (pocket) nets, suspended on submerged longlines; and 2) earhanging to form 'chaplets'. Pocket panels are most commonly used for oysters following grafting; this keeps oysters separate, one oyster per pocket, and optimises rearing conditions (Haws, 2002; Johnston *et al.,* 2018).

The observed natural occurrence of pearl oysters in Bermuda implies a regular spatfall which lends itself to a first pilot study on pearl production using oyster spat (juveniles) collected from the wild. For a full scale operation, source of oyster spat can be obtained from a land-based hatchery. A minimum of 100 broodstock to start hatchery production should be available locally, but needs to be confirmed.


Seagrant (2012)

Hawes (2002)

Seagrant (2012)

Figure 5. Farming technologies for growing oysters (from left to right), trays for juvenile oysters; pocket panels for 'seeded' oysters; earhanging in chaplets; raising suspended longlines for maintenance and harvest.

Market demand and product type:

Pearl farming is an attractive business venture; it produces a lightweight, non-perishable product with high value. Value varies greatly, based on several factors, such as pearl type (or origin), size, colour, shape, luster, surface quality, thickness and size.

Akoya pearls produced in Japan and China are one of the most highly valuable pearls, sold from $100 to $6,000 per pearl (*pearl-lang.com*). Generally, one oyster will produce one pearl, and only a percentage of each crop of pearls (5%-50%) will be of high gem quality (Haws, 2002; Otter *et al.,* 2017). Production of high quality pearls is only possible under certain conditions, including access to grafting technicians, and the ability to market pearls. The process of selling pearls can be a lengthy and complicated process and the reality of introducing a new Bermuda pearl to the market should be explored thoroughly. Potential market for Bermuda-grown pearls includes the export market, given its high value.

The added process of 'seeding' or 'grafting' an oyster to stimulate pearl production is a fixed cost, which dictates the production of a minimum oyster stock ready to graft. As a guideline, an estimated 3,000 pearl oysters is recommended for a profitable farm of the black-lip pearl oyster *P. margaritifera* in Hawaii (Haws, 2002).

Pearl oyster meat is potentially a by-product of *P. imbricata* pearl culture. Bermuda domestic market is non-existent for this species, which has a low meat weight (20 g compared to 35 g for widely consumed American oyster). Domestic market demand for this oyster meat product is unknown at this time.

Production yield:

As for scallops, production yield is estimated based on stocking and harvest density reported in the literature, and is a first step towards assessing production carrying capacity (section 2.1). In order to maintain a pool of 3,000 pearl oysters of suitable size and condition to graft every 18 months, the total farm size would typically need to have 12,000-15,000 pearl oysters in various stages of culture (spat, grafting size, grafted) (Haws, 2002). Oyster juveniles produced in the hatchery are cultivated at densities higher than that used for scallops; trays or bags are suspended on longlines. For the grafting phase, oysters are reared in lower densities. Based on the literature, approximately 1/5th of the farm area is dedicated to grafted and 'seeded' oysters. An estimate of production yield is derived from this information and given in Table 3.

Table 3. Estimated production yield and time to pearl harvest for Atlantic pearl oysters in Bermuda.

Bivalve species	**Stocking density range**	**Harvest density**	**Harvest size (mm)**	**Harvest meat weight (g)**	**No. of oysters /100m longline**	**Time to graft (egg to adult)**	**Time to pearl harvest**	**Total time to market**
Pearl oyster	Phase 1: 16,000 2mm oyster seed/tray Phase 2: 20 'seeded' 70mm oysters/chaplet	Phase 1: 250 adult oyster/tray Phase 2: 1-10 pearls/chaplet	70 mm oyster	20	Phase 1: 2,400 oysters for grafting/longline Phase 2: 1,000 'seeded' oysters/longline; 50-500 pearls/longline	12-18 months	6-18 months	18-36 months

3.1.3 Suitable areas for shellfish farming in Bermuda

Scallop and oyster culture require suitable sites for both a land-based hatchery (seed production), and a farm site in natural waters (market size production).

This section identifies the physical carrying capacity of sites and quantifies potential adequate and available areas for farming; this excludes consideration of other limitations (environmental, economic and social) for a mariculture operation.

Criteria for farm sites suitable to bivalve culture are generally:

- At least 10m deep,
- Protected from storms,
- Support natural food availability
- Well oxygenated water
- Good water flow, but low current velocity
- Bottom type facilitating anchoring and excluding seagrass/corals

Seawater characteristics for farm sites in other regions culturing scallops and oysters is given in Table 4. The higher end of the turbidity range given for scallop species was associated with mortalities (Agguire-Velarde *et al.,* 2019; Rupp *et al.,* 2005). Food availability is indicated by phytoplankton mass (chlorophyll a) and availability of particulate organic matter in the water column (POM). Seston indices reflect the dilution of the organic component (POM) by the inorganic (PIM), or the percent PIM present. Reduction in scallop growth has been associated with a 3.5 PIM:POM value, representing 78% PIM of total seston (Rupp *et al.*, 2005).

Table 4. Environmental variables recorded for scallop and pearl oyster species cultured in suspension.

Species	**T (°C)**	**Salinity (ppt)**	**Chl a (µg/l)**	**PIM (mg/l)**	**POM (mg/l)**	**Total seston (mg/l)**	**Turbidity (NTU)****	**O2 saturation (%)**	**Current velocity (m/s)**	**Source**
Argopecten purpuratus	16-24	33-36	5-30				1-3			Agguire-Velarde *et al.*, 2019
Nodipecten nodosus	20-28		1-10			10-60				Lodeiros *et al.*, 1998
Nodipecten nodosus	16.1-28.4	30.3-33.7	0.77-1.7	1.5-5.5 (73.4-81.6%)*	0.5-1.5		0.77-4.48	88.7-95.1		Rupp *et al.*, 2005
Placopecten magellanicus									<0.9 and >0.16	Claereboudt *et al.,* 1994
Pinctada imbricata radiata	13-30	36.86	0.528-6.884	0.62-7.45	2.45					Yigitkurt *et al.,* 2020
Pinctada imbricata	7-30.8		<1-5			<30-60				Lodeiros *et al.,* 2002
Pinctada margaritifera	25.5-28.5		0.3-1.8 Mean 0.7							Lacoste *et al.*, 2014

*PIM as percentage of Total seston
**NTU (Nephelometric Turbidity Units)

Oysters are better able than scallops to compensate for the dilution of POM by PIM, enabling them to tolerate more turbid areas. Oysters also differ in that they consume more than tenfold scallop food ration, and larger species of pearl oysters are reported to clear up to 18.7 liters/g /hour of plankton (Fournier *et al.,* 2005). This high food consumption also results in a higher faecal/pseudofaecal production, and entrains a high organic biodeposition beneath cultured stocks, which can negatively impact the environment. For these reasons, oysters are generally cultured in environments with relatively higher food availability and high flushing rates (the amount of time for the complete exchange of water). A rapid exchange of water minimises the impact of oyster farming on the environment, by distributing the amount of organic biodeposition across the seabed.

Environmental layers used to identify areas in this document are: Depth, temperature, salinity, dissolved oxygen, natural food availability (indicated by chlorophyll a), turbidity, and residence time. Bermuda inshore water sites are characterized by wide seasonal fluctuations in seawater temperature, a constant high salinity, and relatively low dissolved oxygen and chorophyll a (chl a) levels. Natural food availability is comparable to other sub-tropical/tropical sites where culture of bivalves is successfully carried out (Table 4). Studies on other bivalve species in Bermuda report minimum winter temperatures as the limiting factor for growth and reproduction, rather than food availability (Sarkis, 1992). The high flushing rate in Castle Harbour is advantageous for large scale oyster production; the ecological carrying capacity and its ability to support a high volume of oysters at any one time is unknown at this time.

The 5-year Bermuda pilot scale scallop culture programme evaluated shell growth in several inshore bodies of water: Harrington Sound, Agar Island, Little Sound (Riddell's Bay Golf Course), Bailey's Bay (North shore side), Castle Harbour, Ferry Reach. The best results in terms of shell growth and roe development was Harrington Sound; Castle Harbour supported good shell growth, but roe and muscle weight were not comparable to Harrington Sound (S. Sarkis, *unpub.*).

Seawater characteristics and surface area for selected sites are given in Table 5. There are 3 areas identified in Harrington Sound amounting to a potential culture area >1 km^2 ; 2 areas in Castle Harbour, for a potential total culture area of 4 km^2, and one in Bailey's Bay of 0.2 km^2. Harrington Sound is recognized to be one of the most productive bodies of inshore waters in Bermuda, due in part to its high residence time; chl a values representing food availability peak at 3.13 µg/l in Harrington Sound compared to Castle Harbour at 1.5 µg/l. Bailey's Bay is a small, shallow site with a recorded low food availability; it is included here as an additional holding site for juvenile bivalves (<25mm). Distributing stock in more than one area is a good risk management approach. Particulate organic matter is an additional source of food for scallops and oysters, but there is no data available for selected sites.

Table 5. Site characteristics relevant to suspended culture of bivalves; seawater characteristics (range) compiled from datasets by Fourqurean et al. (2019), Hochberg (2004-2011), WQMP (2007-2012), and S. Sarkis (1992)

Site	Average depth (m)	T (°C)	S (ppt)	DO (mg/l)	Chl a (µg/l)	Turbidity (NTU)	Residence time	Site #- Surface Area for culture (km^2)*
Harrington Sound	14.5	15.1-31	36.3-37.2	5.6-8.0	0.06-3.13 Mean 0.8-1.8	0.29-1.1	Mixed layer- 6 days Entire sound- 29.4 days	1- 0.466 2- 0.135 3- 0.532
Castle Harbour	8	14.8-30.6	36.1-36.9	5.9-7.3	0.09-1.5		1-4.1 days	4- 2.335 5- 1.719
Bailey's Bay	4	16.9-30.4	36.1-37.3	5.5-9.3	0.09-0.47	0.2- 0.97	<3 days	0.209

* *Surface area was estimated by S. Brooks (Ted Waitt Institute); site numbers refer to arbitrarily labeled mapped area (BOPP)*

Theoretically, a 0.5 km^2 grid accommodates 8 longlines, 100m each, and 20 m apart to prevent entanglement; this will support scallop stocks from 4 mm shell height to market size; in Castle Harbour, the larger surface area for each site should accommodate at least twice the number of longlines. Practically, the bathymetry, sediment morphology and type, shape of bottom surface area and other uses of the area will affect the total number of longlines installed, and must be considered during the final site selection process.

Selected bivalve farm sites are mapped in Figure 6. In Castle Harbour, the surface area available for suspended cultures is 4-fold that of Harrington Sound, expanding the scope of production for bivalves (Table 5). The pale colour of scallop roe grown in Castle Harbour observed during previous studies imply a sub- optimal environment; this concurs with reduced food availability (Table 5), fluxes of high sedimentation (up to 3.14 mg/cm^2/day; Flood *et al.,* 2005), and/or high storm wave action, which are all limiting factors to bivalve growth. The level to which this limits product quality and production volume is not known at this time and can be investigated through pilot studies.

Careful selection of farm sites in Castle Harbour is necessary as the dumping of bulk waste and cement-stabilised ash from the island's municipal incinerator borders the northwest shore. It is recognized as a significant potential source of marine contaminants to Castle Harbour. Several studies confirm the localized metal enrichment in sediments near the dumpsite, and a rapidly decreasing gradient in heavy metals and organic compounds levels with increasing distance from the dump; levels ultimately reach negligible levels at 150 m from the dumpsite. Sites identified here are not reportedly affected by this point source of pollution (Duplaga, 1992; Burns *et al.*, 1992).

Figure 6. Potential inshore sites for suspended cultures of scallops and oysters in Bermuda. Left: Harrington Sound (3 sites), Bailey's Bay (on North Shore, top left); Right: Castle Harbour (2 sites). (S. Brooks, M. Paufve, Waitt Institute).

Both Harrington Sound and Castle Harbour sites offer advantages and disadvantages which must be weighed against a species' tolerance. Harrington Sound offers the benefits of: 1) High food availability, and 2) protection from storms. The main limitations relate to: 1) Available space, and 2) high residence time; this reflects a slow exchange of water, which may result in the accumulation of organic biodeposition by a large scale oyster culture operation, and the increase of nutrient input. In turn, this may trigger potentially harmful algal blooms. The major benefits of Castle Harbour are: 1) Large surface area, and 2) low residence time – or a rapid flushing of water- which assists in dispersing organic material accumulated below oyster cultures and minimises associated environmental impacts. The main limitations in scaling production in Castle Harbour are: 1) Exposure to hurricane winds – this can be partially addressed by submerging longline systems, at least 1 m below the surface- , 2) low food availability (chl a) compared to Harrington Sound, and 3) high turbidity and sedimentation during high winds.

The suitability of offshore and more exposed sites for scallop and oyster culture is uncertain. Although offshore technology is currently considered overseas, this technology remains in its infancy; it is not feasible to simply copy the inshore system design, with heavier materials. New developments require a technological revolution, for new structures to remain stable and robust in high energy situation, with associated higher capital costs; there is currently no such recipe for offshore bivalve culture. The additional limiting factor offshore for bivalves relates to food availability. Bermuda's inshore waters undergo more intense phytoplankton blooms supported by nutrient input from proximity to land; reduced food availability offshore may be a limiting factor in achieving growth rate, time to market, and/or development of roe. Alternatively, integrating the farming of oysters, which generally exhibit a higher tolerance to wave action found offshore than scallops, with an offshore cage finfish culture operation will enhance food available to shellfish through the generation of organic matter by finfish (see section 7, IMTA).

3.2 Finfish (High Trophic): Culture, market and production

Finfish species identified here are carnivorous fish and require the daily input of feed from larvae to market size. This leads to a marked difference with culture methods for bivalves during the farming stage and has been the subject of intense criticism by environmental organisations as a threat to coastal ecosystems, deemed unsustainable with a substantial 'fishprint'. Advancement in technology has reduced this 'fishprint' by addressing several of the contentious issues; one of these is creating a shift from coastal (or nearshore) to offshore farming systems, the second is the development of fully integrated land-based systems (RAS). All finfish species selected in this document lend themselves to both technologies. However, this document focuses on identifying spatial requirements for offshore culture technology and provides details for this type of cultivation system only.

3.2.1 Snappers, *Lutjanidae*

Most snapper species have similar culture techniques, farm site requirements, production yields and environmental concerns; in Bermuda, lane snapper, *Lutjanus synagris,* and mutton snapper, *Lutjanus analis* are the most likely candidates. Lane snapper is a confirmed native species and first choice. The mutton snapper was introduced in the 1920s [2], and although occasionally caught by commercial fishermen, it is considered rare in Bermuda waters (T. Warren, *pers.comm*.); this may exclude its use for commercial culture, but is included here because of its ease of culture and similarity in taste and appearance to the highly prized red snapper.

Note: Snappers undergo natural hybridization, and confusion among species is common. Rigorous identification of snapper species selected is a must before starting an operation (D. Benetti, *pers.comm.)*

Culture techniques and source of juveniles:

Culture techniques for the spawning, larval rearing, fingerling production, and farming to market size of both species are developed at pilot scale in the Caribbean Region (Florida and Puerto Rico, 2002). Market size for snappers is reached in 12 months. Hatchery techniques to rear juveniles from eggs can utilize recirculating aquaculture technology (RAS).

There are two approaches to obtaining a source of juveniles: 1) Collection of local broodstock for spawning in a land-based hatchery, and/or 2) purchase of fertilized eggs or larvae from operational overseas hatcheries- for example, the University of Miami aquaculture Centre produces hatchery eggs and fingerlings for supply to commercial operations. For a hatchery-based operation, broodstock are usually collected from natural local stocks. Snappers are commonly found in Bermuda, and it is anticipated that broodstock collection by hook and line or trap is possible. Targeted broodstock size is 47 to 45 cm total length, and 1.58-2.04 kg total weight. Yearly production is optimized through breeding programmes extending natural spawning season. Initial purchase of eggs or fingerlings enables an R&D phase adapting techniques to Bermuda and demonstrates the feasibility of commercial scale culture. A land-based facility will be needed to carry out spawning and/or grow juveniles for 2-3 months before transfer to the farm, regardless of whether the source of juveniles is local or imported.

Farming of juveniles to market size has been tested offshore with promising results (Snapperfarm Inc., Puerto Rico, 2002); it was not pursued commercially as cobia performance (time to market and size) outweighed that of snappers. Feeding Conversion Ratio (FCR) is a key factor in finfish culture; it indicates feeding efficiency and is calculated as feed given/animal weight gain. FCR is species dependent and varies according to type of feed, seawater temperatures and farming practice. Poor feeding management leads to cannibalism in some species (amberjack), competition for food in cages, and proliferation of opportunistic pathogenic bacteria; this can result in up to 20% loss of stock (Benetti *et al*, 2010). FCR for mutton snapper is reported at 1.4; this indicates that 1.4 kg of feed is required for every 1 kg of fish produced. This is lower than FCR reported for amberjack grown in the Mediterranean approximating 2-2.5, and that for cobia estimated at 2-3. Feed costs in a finfish aquaculture operation are substantial, and generally represent at least half of the total budget of the

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[2] The introduced naturally occurring but rare status of the mutton snapper does not comply with current Bermuda policy on aquaculture. Culturing of this species depends on the final assessment of the Department of Environment and Natural Resources (Government of Bermuda).

farm. Snapper survival rates from juvenile to market range between 60-85%, and are dependent on several factors, which can be improved through best farming practices.

Market demand and product type:

Commercial landings of snappers in Bermuda averaged 44 mt over a 5 year period- 2013-2018 (DENR, 2021); lane snapper was the most caught fish, both commercially and recreationally, and regulations enforce a recreational bag limit of 30 lane snappers/day. Domestic market price for snappers is \$16.18/kg (\$7.34/lb).

Snappers are also popular fish in the US, with peak commercial landings in the southeastern US recorded at 10,000,000 pounds (4,800 metric tons) in 1998, and a dockside value of \$10,000,000 (NOAA fisheries). Landings do not meet the demand, and US imported 25 million pounds (11,000 mt) of snapper from the Caribbean and Gulf of Mexico in 1998, valued at \$38.7 million (fisheries.noaa.gov). U.S. filet prices reach \$12/kg (seafood source, 2021). Red snappers are the most highly prized snapper species, but do not regularly occur in Bermuda waters (J. Pitt, *pers.comm.).*

Market size of snappers (1kg, and up to 40 cm length), is small compared to other cultured species such as cobia or amberjack. For this reason, the whole fish is recommended as a preferred market product. Other products are dressed or cleaned fish, fresh steaks, fillets and loins, frozen (kept up to 6 months).

Production yield:

Production yield is estimated based on stocking densities and target market weight recorded in research and pilot scale operations in the Caribbean (Table 6). Stocking and harvest densities are species and site dependent; stocking densities of 15 kg/m^3 are common for several finfish species. Snapper growth and survival is reported to improve with a lower stocking density. For 10 g fingerlings stocked at 25 fish/m^3, a harvest density of 25-30 kg/m^3 is obtained for a cage of 300 m^3 (Benetti *et al.,* 2010). Final harvest can be projected at 7,200 (1kg) fish for a 300 m^3 (7.2 mt/cage) within 10 months of farming.

As for all species, total production potential depends on carrying capacity of farm site and surface area available for culture.

Table 6. Production estimated for snapper cage culture, based on harvest density per cage (300m^3).

Finfish species	**Stocking density range (seed/juveniles)**	**Harvest density**	**Harvest Total weight (g)**	**No. of market size fish / cage**	**Harvested metric tonnes/cage**	**Time to market (egg to market)**
Snappers	25 fish/m^3 or 3 kg/m^3	25-30 kg/m^3	1kg	7,200	7.2	12 months

3.2.2 Almaco jack, *Seriola rivoliana*

Culture techniques of almaco jack, *Seriola rivoliana*, are well developed and currently applied by Blue Mariculture - a fully integrated private commercial scale operation producing market size fish off the coast of Hawaii. Although, techniques used are not shared publicly, this operation is a potential source of fertilized eggs, technical support and/or partnership. To our knowledge, this is the only commercial operation of almaco jack at the time of writing.

Culture techniques and source of juveniles:

Hatchery and nursery requirements for rearing almaco jack juveniles are similar to those described for snappers; the difference is in the greater tank/cage volume required for this species due to its larger size. Reproduction in captivity is challenging, and several operations need to retain breeders in cages utilizing natural environmental conditions rather than controlled hatchery conditions. This implies a seasonality in spawning and consequently in juvenile production. *S. rivoliana* is reported to adapt readily to rearing conditions and to dry commercial feeds.

Amberjack species can be farmed in offshore cages (6,400 m^3 and up) or in smaller Japanese style floating net pens ranging in size from 125 m^3-1000 m^3. The Japanese technology is strong enough to withstand tides and typhoons, but requires a large surface area in nearshore waters for floating rafts; these surface enclosures are more conducive to fouling than submerged cages and are labour-intensive (Sicuro and Luzzana, 2016). One major consideration specific to amberjacks is the availability of space sufficiently large to exercise; this helps in building firm muscle and produce high-quality meat. This spatial requirement affects stocking density, which depends on cage size and current velocities; the greater the cage and the stronger the current, the higher the stocking density. Cage culture growth for *S. rivoliana* is reported to produce 2.7 kg fish in 15 months (egg to market) in Hawaii (Blue Mariculture, *pers.comm.*). Amberjacks are in general vulnerable to skin infestations, and best management practice with routine sampling and treatment in farm sites are mandatory for a reliable production.

Almaco jacks are considered common in Bermuda, and it is likely that a broodstock could be obtained from natural populations. An alternative strategy to bypass the broodstock phase, is the purchase of fertilized eggs from existing hatcheries- Blue Mariculture (Hawaii), University of Miami (Florida) are two potential sources at the time of writing. RAS systems are also used to culture amberjacks, similar to snappers and Cobia (InnovaSea, *pers.comm.*).

Market demand and product type:

Amberjacks generally are in high demand, and the flesh is much appreciated by consumers, especially for sushi and sashimi. Meat quality for sashimi products calls for a correct fat level (10% fat). Prices range dependent on flesh quality from \$9-\$18/kg in Europe and fetch up to \$20-\$30/kg in Japan (Papandroulakis*,* 2018). Fresh fish is cold-stored for no more than 3 days, for sashimi products (storage time depends on rearing conditions and post-harvest treatments).

Production yield:

Stocking density for a pelagic fish, such as almaco jack, is lower than for cobia or lane snapper; it approximates 5 kg/m^3 for 20 g fish, and is further reduced in Japanese culture systems to 1.2-1.5 kg/m^3 for 3.5-4 kg market size animals (FAO, 2021). For target market size amberjacks of 4 kg, this translates into 54 mt/3000 m^3 cage, or 115, 2 mt/6400 m^3. Increasing the size of offshore cages, up to 8,000 m^3, allows for an increase in stocking density up to 35 kg/m^3. Risk and profit are counterbalanced by harvesting at a smaller size (2.7 kg) (Blue Mariculture , *pers.comm.*). The Japanese net pen culture and frequent grading is reported to yield a 90-97% survival rate from 0.5-10g range to market weight. Unfortunately, these numbers reflect a specific cultivation method, which is unsuitable to Bermuda because of its floating cage culture system, its reliance on wild-caught juveniles, and its daily usage of raw fish as diet. There is no available information on survival rate for offshore cage culture.

Estimated production per 3000 m^3 cage is 45-60 mt, based on data by Sims (2013); this is derived from conservative stocking densities and market size of 3 kg (Table 7). Breakeven point for an almaco jack aquaculture operation based on an offshore farming case study is reached at 1,000 mt production/year (Sims, *pers.comm.*). This would require a minimum of sixteen 3000 m^3 cages using data in Table 7.

Table 7. Production estimated for almaco jack offshore cage culture, based on harvest density per cage (3000 m^3).

Finfish species	Stocking density (seed/juveniles)	Harvest density	Harvest Total weight (kg)	No. of market size fish / cage	Harvested metric tonnes/cage	Time to market (egg to market)
Almaco jack	5 kg/m^3	15-20 kg/m^3	3kg	15,000-20,000	45-60	16 months

3.2.3 Offshore Cage Culture Technology for prioritised finfish species

Finfish culture has been traditionally conducted in nearshore environments; this is now recognized to have substantial impact on nearby sensitive ecosystems, such as coral reefs, caused by the increase in organic matter recorded near fish cages. With advancing technology, the shift is towards offshore or open ocean culture - where current velocity and distance from sensitive ecosystems mitigate the accumulation of organic matter by enhancing dispersion of farm-generated wastes over a wider area. This comes at a high technological cost. Fingerlings are stocked in cages ranging from 300 m^3 to 14,500 m^3, and fed daily until they reach market size. One of the largest offshore operations producing cobia (Open Blue, Panama) reports intensive maintenance of cages and fish stock, up to 60 trips/month to prevent disease infections and fouling of cages. This farm is serviced by a semi-permanent feed barge/security platform vessel. Automation is used throughout the operation, especially during feed and harvest; for example, pelletized feed is provided to the fish via a pumping system that delivers feed to the fish through extended hoses connected to feed boats. A separate harvest boat (>20 m) transports harvested product back from the farm site to land. Several other smaller work boats are also used to support net pen and grid maintenance and cleaning, and other tasks. A schematic representation of all activities necessary to the operation of a large scale offshore commercial finfish culture operation is given in Figure 7.

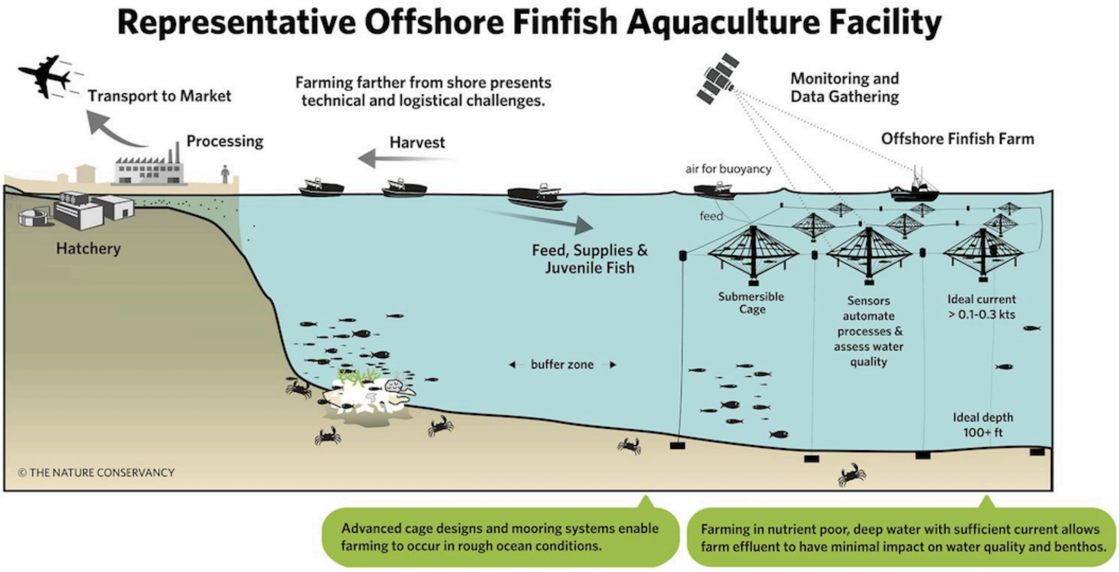

Figure 7. Representative offshore finfish aquaculture facility based on hatchery production of juveniles, showing offshore system for juvenile to market size, processing and transport to market. (TNC).

Cages can be flexible or rigid, submersible, semi-submersible or floating, made of netting material resistant to environmental conditions, with an arrangement of grids and moorings, and anti-predator devices, improved anti-fouling technologies and automated fish mortality removal equipment. There are several manufacturers of cages for offshore operations; one example is given here, used in exposed sites similar to potential Bermuda sites (cobia farm-13 km from shore 80 m depth; almaco jack farm – offshore Hawaii 65 m depth) (Fig. 8A). This 6,400 m^3 cage consists of a 24 m central spar, and an exterior rim with a diameter of 35 m circling the spar at midpoint. Netting (rigid Kikko with high tensile strength 45 kN/m) is stretched over the frame, and reportedly provides sufficient resistance to withstand predator (shark) tears, and entanglement by mammals.

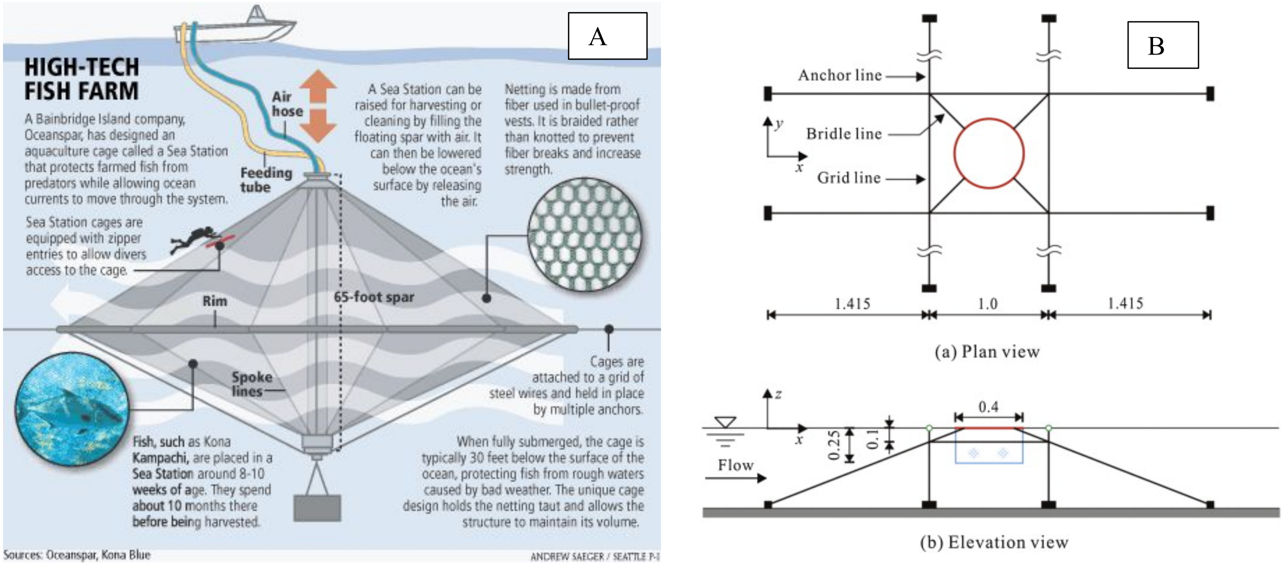

Figure 8. A: Sea Station schematic designed and used for offshore finfish cage culture. (Kona Blue); B: Schematic grid system for anchoring of offshore cage with series of buoys and weights keeping lines taut. (Xu et al., 2013)

Cages are moored with multi-point moorings, secured within an anchor grid and can be maintained submerged; Figure 8B illustrates a schematic grid system anchoring each cage. Based on a pilot case study, the installation of eight 3000 m^3 cages in a surface area of 0.36 km^2 requires 14 anchors and mooring weights. A similar system has reportedly survived Category 3 and 4 hurricanes (Sims, 2013).

3.2.4 Suitable areas for finfish offshore cage culture in Bermuda

Finfish culture requires a) a land-based nursery to receive eggs, and rear larvae and fingerlings, and b) a farm site with cages for grow-out to market size. Requirements for a land-based facility in terms of water usage are:

- An incoming source of clean seawater,
- Easy access to farm sites.
- Several moorings and dock space for service boat, feed boat, harvest boat
- Processing plant (packing and shipping)

Site selection for the farm is key and must take into account the operation's impact on the environment more closely than for bivalves. Open ocean offshore aquaculture uses advanced farming systems, methods and equipment that can withstand the elements; they are often placed in strong current areas with greater depth to increase carrying capacity for nutrient assimilation and reduce point source pollution (Benetti *et al*., 2010). By international law, 'offshore' sites refer to 'sites beyond 3 nautical miles (or 5.5km) from shore. The term 'open ocean' rather than 'offshore' is used in the Caribbean because distance from shore is often <5.5 km, yet oceanic conditions prevail and sites are usually subject to high-energy conditions (wind, waves and currents). This is the case for Bermuda, and several sites identified here <5.5 km are comparable to offshore conditions. Offshore finfish aquaculture is more expensive than nearshore marine aquaculture, estimated at 15-30% higher in cost than conventional production, barring exponential increases in scale (CEA, 2018).

Environmental layers used to identify finfish areas are: Depth, temperature, salinity, current velocity, and residence time. Technical constraints to the aquaculture operation are also included. These are:

- Distance to reef- to eliminate risk of impact from cage culture
- Distance to shore – time for transport to and from hatchery and processing; maintenance time; determines operational costs (stocking cages, harvesting, distribution to market; proximity of support services such as fuel, slips).

Sea station cages are ideally installed in 60-100 m depth, mostly because of their size (6,400 m^3); smaller cages (averaging 300 m^3) can be deployed in shallower waters (40-60 m). The system is normally kept fully submerged and is ideally deployed in areas with year-round strong wave activity. Cages can be brought to the surface for maintenance or harvesting. When submerged, the top of the spar is at 10 m depth, or greater.

There is no site specific data for current, temperature or salinity available; however, baseline data is obtained monthly at various offshore sites as part of BIOS's oceanography programme. Temperature range and salinity in these areas approximate 18-30°C and 36 ppt respectively (Johnson *et al.,* 1998). Current velocities averaged over the full water column (0-200 m) offshore are typically semi-chaotic driven by oceanic mesoscale eddies with magnitudes of 20-50 cm/s (0.4-0.9 knots) with no prevailing direction (Johnson *et al.,* 1998; Venti *et al.,* 2012). Velocities are comparable to existing cobia farm sites (0.05-0.7 m/s; 0.1-1.3 knots), but lower than in a previous pilot operation off Puerto Rico (0.5-1.9 m/s; 0.9-3.7 knots; 27 m depth). Concerns were raised at this latter site that currents of 0.5 knots did not effectively flush the accumulation of organic matter from excess feed and faecal deposition by fish, and provide the necessary water exchange inside fish cages (Alston *et al*., 2005).

On the other hand, residence time models for Bermuda clearly demonstrate a decrease in residence time extending seawards; residence time ranges from 12 days inshore to 1.4 days at the rim reef, and offshore of 12 hours (Johnson *et al.,* 1998); this indicates that outer reefs are replenished with offshore water every new tidal cycle and implies that the chance of having any sustained impact of organic deposition by cage culture is minimal.

A total of 11 sites has been identified around the Bermuda platform which fall within the depth range criteria (Table 8; Fig. 9). Table 8 indicates depths, surface area for each site, and the technical constraints defined above.

Table 8. Depth, proximity to shore and reef, and surface area for sites potentially suitable for offshore cage culture in Bermuda (M. Paufve, Waitt Institute).

Site	**Depth range (m)**	**Distance to reef (km)**	**Distance to shore (km)**	**S.A. (km^2)**
1*	47-149	37	45	52.3
2*	42-168	17	26	54.1
3	37-85	3.7	17	3.5
4	40-124	3.9	17	1.9
5	26-179	1.7	13	1.3
6	30-145	1	12	0.7
7	34-133	0.5	18	2.2
8	35-136	0.3	1.8	3.4
9	33-104	0.2	2.8	2.2
10	35-87	0.3	3.3	1.1
11	34-104	0.2	4	2.2

Depths are estimated to range from 26-179 m (Table 8); higher resolution is required to specify depth contours within given areas for final site selection; detailed bathymetry will also be required, as factors such as steepness of slope will affect bottom area available for securing of anchors. Surface area for sites 3-11 ranges from 0.7- 3.5 km^2; dependent on the suitability of physical/chemical and biological parameters, site 6 with the smallest surface area may not satisfy the minimum surface area for a suggested breakeven point (1000 tonnes of fish/annum; section 3.2.2). Sites 1 and 2 pose further logistical challenges due to their distance from Bermuda's landmass (>15km; Table 8; Fig. 9), and potential multi-use conflicts with existing fishing activities. Sites 8,9,10 and 11 require additional consideration as whales are a frequent occurrence during migratory season, and entanglement in finfish cages may be of concern.

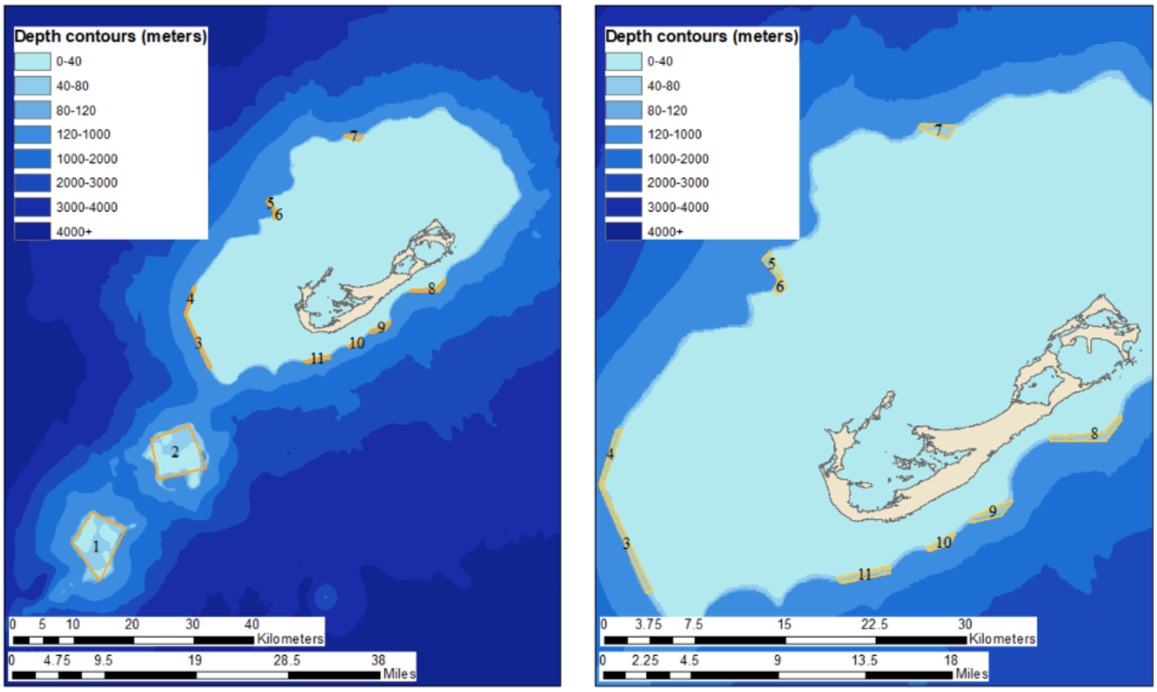

Figure 9. Sites around Bermuda with depths range approximating 30-180m. Compiled by Matt Paufve (Waitt Institute).

4. Environmental Concerns: Level 1 Species

Environmental concerns address both hatchery-based activities and farm-based operations. Hatchery-based environmental issues are often associated with the import of organisms (broodstock or seed/fingerlings), and waste discharge. The most notable impacts result from farm-based operations. Description of environmental concerns for prioritised species (Level 1) are given in Appendices II, III, and IV. These are summarised in Table 9 and provide a comparison among Level 1 prioritised species; where relevant, Best Management Practice (BMP) is noted as a mitigation tool (see details for BMP in Appendix V).

In general, marine bivalves as herbivores are considered a sustainable type of food production; this usually results in low impacts to the surrounding marine environment (Capelle, 2020). Recorded impacts are associated with high stocking densities; controlling these through best management practices while achieving profitability is an important factor for the overall sustainability of a marine aquaculture operation.

There is little available data that demonstrate negative impacts on the environment as a result of bivalve aquaculture; any concerns are usually associated with oyster farming rather than scallop farming. These can often be mitigated through rigorous site selection and Best Management Practice; this has been demonstrated by minimal effects assessed with respect to several seawater parameters (dissolved oxygen, turbidity and chl a) from oyster farms with low stocking densities and relatively high flushing rates (Turner *et al.,* 2019). It is noteworthy to add that bivalve farming – oysters in particular- can also have positive impacts on the environment by removing excessive nutrient through

Table 9. Summary of environmental concerns related to hatchery and farm-based activities for prioritised bivalve and finish species.

	SCALLOPS		OYSTERS		FINFISH	
Environmental concern	**Projected Impact by activity**					
	Hatchery	Farm	Hatchery	Farm	Hatchery	Farm
Feed	Negligible	nil	Negligible	nil	Low- if 'food fish' sustainably sourced; BMP for alternative food sources	High- due to large volumes of feed used; must be sustainably sourced; shift towards alternative food source as BMP to reduce pressure on natural 'food fish' stocks
Genetic impact on wild stock	N/A	Negligible	N/A	Negligible	N/A	Low - if BMP applied to maintenance of cages and breeding programme
Interactions with wild fish	N/A	N/A	N/A	N/A	N/A	Nil- Fish aggregating nature of cages; no impact reported
Source of stock	BMP for broodstock import	N/A	Nil	N/A	Low- if broodstock removed from abundant wild stock; BMP for fertilized eggs import	N/A
Competition for food	N/A	Nil	N/A	Low-High; dependent on scale of culture operation	N/A	N/A
Effluents	Negligible	N/A	Negligible	N/A	High – if effluent not treated	N/A
Water discharge	Low- use of BMP for broodstock Nil - for larvae and spat	Negligible- if carrying capacity is not exceeded	Low- use of BMP for broodstock Nil - for larvae and spat	Low -in areas of high flushing rate, Negligible- if carrying capacity is not exceeded Low- if BMP used for longlines and sites	High - but manageable at high costs	Low - if located in area of high current velocity. Current velocity required
Antibiotics	Negligible	Nil	Negligible	Nil	Negligible- if regulated	Negligible- by using BMP
Escape risk	N/A	Negligible	N/A	Negligible	N/A	Low- if BMP mitigation through maintenance of cages/netting . No record for snappers and amberjack.
Introduction of alien species	Low- if BMP for broodstock import	N/A	N/A	N/A	Low- if BMP for fertilized eggs import	N/A
Disease interactions	Nil	No reports	Nil	Low- No reports on impact of cultured stock on wild	Nil	Low- No reports; BMP to reduce risk
Impact on habitat and benthos	N/A	Negligible - by installation of anchors	N/A	N/A if appropriate site selection away from sensitive ecosystems; Negligible- for anchor	N/A	Low;-one time anchor impact during installation
Entanglement of marine mammals	N/A	N/A	N/A	N/A	N/A	Low- No reports of entanglement with adequate tensile strength

**BMP refers to Best Management Practice* assimilation or benthic denitrification; this process is dependent on seasonal processes and site. This type of ‘restorative aquaculture’ is an increasing trend in areas where eutrophication is of concern; oyster farming is also used in conjunction with finfish cage culture farming, as oysters exert control and mitigate nutrient input by fish culture stocks (Carranza and Ermgassen, 2020).

The most dominant environmental concerns are related to finfish cage culture; the nature and magnitude of effects largely depend on site-specific conditions relating to the species feeding requirement, intensity of farming, flushing characteristics of the environment, and the proximity of the farm to valued habitats (*e.g.* coral reefs) and species (*e.g.* nesting shorebirds). These impacts are most evident in nearshore finfish culture because of the associated high impacts on coastal ecosystems through eutrophication and potential harmful algal blooms. The selection of cultivation technology plays a role in reducing potential impacts; offshore farm technology discussed here, is one alternative, the use of RAS technology (land-based recirculating aquaculture) is another.

First and foremost good site selection can reduce the potential environmental effects of marine fish farms. Beyond this, is the use of integrated multi-trophic aquaculture (IMTA), which can be used to further reduce specific environmental effects (see Section 7).

Environmental impacts for a full-scale operation can be assessed through pilot studies. This is achievable for shellfish culture, but difficult for finfish culture due to the high baseline capital investment required for offshore technology. However, Bermuda benefits from a long-term time series oceanography database (BATS, Bermuda Institute of Ocean Sciences) which assists in estimating the level of consideration given in Table 9.

5. Priority Level 2

Level 2 species are those with a demonstrated alternative system to ocean-based farming, potentially of higher suitability to Bermuda’s environmental conditions. The Queen conch is traditionally cultured on shallow sandy bottoms (<4 m) in fenced areas close to shore (Sarkis and Ward, 2009.); there is limited space for this type of culture in Bermuda. Cobia shows optimum growth at seawater temperatures above 20°C (Thomas *et al.,* 2009; Kaiser and Holt, 2005), and there is concern that time to market would be increased up to 48 months under Bermuda’s low winter seawater temperatures. Both are species with proven technology and a market demand, and both have demonstrated adaptability to land-based systems.

5.1 Alternative cultivation technology: Land-based and RAS systems

Land-based systems for growing animals to market size require a substantial land area, infrastructure and skilled personnel. Systems can be open flow, semi-recirculating, or full recirculating aquaculture systems (RAS). While RASs are often much more expensive to build, maintain and operate than other methods, organisms can be raised under more ideal water conditions throughout the year. RASs occur in a wide variety of configurations, but the essential characteristic of such systems is that they reuse all or a significant portion of their rearing water multiple time (close to 90%; Schwarz *et al.,* 2017). Several finfish species have been tested in RAS systems, including cobia, almaco jack and snappers; RAS systems are intensive in nature, they generally carry 0.25 to 1 pound of fish per gallon of water (30 to 120 kg/m^3) (Schwarz *et al.,* 2017). The use of RAS technology for farming fish is generally considered the Best Choice by Monterey Bay Seafood Watch programme (2020).

More specifically, the advantages of RASs as a closed system include:

- Control of seawater parameters- such as temperature – enabling constant seawater characteristics required for optimal growth.

- Capacity to capture solids and appropriately dispose of it, as well as to implement denitrification or other soluble waste treatment prevent nutrient input and cumulative ecological impacts on adjacent body of water.
- Strict biosecurity, and physical separation of culture tanks and natural environment – escape of animals, and interactions with wild stocks are prevented.
- Disease transmission risk to wild stock is extremely low due to low discharge of water and ability to treat this water
- RAS systems can utilise previously existing buildings, with no habitat conversion of loss of ecosystem functionality.
- Co-culture of seaweed – effluents from an RAS system contain nutrients generated by fish biodeposition. Experimental work shows that seaweed thrive on waste water; current studies demonstrate high production of *Agardhiella sp.* biomass cultured in discharge water of Japanese flounder (*Hirame sp.*) (D. Benetti, *pers.comm.)* (Fig. 10).

Figure 10. Experimental co-culture of land-based Japanese flounder (Hirame sp.) with Agardhiella seaweed using RAS, University of Miami. Left to right: high density juvenile flounder tank, waste discharge tanks with seaweed, close up of seaweed (photos: S. Sarkis).

5.2 Priority Level 2 Species Summary

Table 10 summarises the rationale, recommended approach, and the qualitative strengths and weaknesses of Level 2 species with respect to their culture potential.

6. Priority Level 3: Bottom culture systems and Research

Species in Level 3 are those:

- Traditionally cultured on the bottom with limited or no knowledge of other farming systems,
- Requiring further research to fill a gap in culture techniques or adapt new technology

There are two major operational challenges to bottom culture: 1) The protection of cultured stock from natural predators and 2) cost-effective maintenance and harvest with minimal impact to the seabed. Large surface areas require submerged fencing secured to the seabed, and harvest is often conducted by SCUBA making this technology logistically challenging and labour-intensive.

6.1 Priority Level 3 Species Summary

Tables 11 and 12 summarises the rationale, recommended approach, and qualitative strengths and weaknesses of Level 3 species with respect to their culture potential.

Table 10. Bermuda species prioritised as Level 2 and suitable to land-based culture systems.

Species	**Rationale for Level 2 prioritisation**	**Recommendations**	**Strengths**	**Weaknesses**
Queen conch (*L. gigas*)	Lack of suitable sites for bottom culture / Slow growing to full size (4-5 years)	Investigate 2 year old market potential (domestic and export)/ Assessment of local broodstock/egg mass/ R&D full land-based production of 2 year old market size/ Financial analysis for 2 year old market	Existing domestic demand/ Potential export	Low natural stock limit egg mass collection/ Market for 2 year old conch uncertain
Cobia (*Rachycentron canadum)*	Anticipated slow growth rate in Bermuda associated with low ambient seawater winter temperatures (18-20°C); increasing time to market possibly twofold if reared offshore	Pilot study RAS system for optimal growth rate/ Financial analysis of RAS production / Market analysis (focus on export market)	Fast growing fish at T > 20° C; 13 months cycle average to market size 3-4kg/ Export market demand (including US East Coast) at US$8.62/kg/ Existing source of fertilised eggs from commercial hatcheries/ Known RAS technology	High FCR up to 3/ Not locally consumed
All finfish species		Comparison of RAS and offshore cage production sustainability (environmental and economic and social)		

Table 11. Priority Level 3 species traditionally cultured on the bottom.

Species	**Rationale for Level 3 prioritisation**	**Recommendations**	**Strengths**	**Weaknesses**
	Bottom culture system			
Sand scallop (*E. ziczac*)	Farming- technology not scalable/ Harvest- labour intensive by SCUBA	A secondary product to existing aquaculture operation	High value/ Fasst growth/ High consumer appreciation locally	Delicate species which can incur high mortality at all stages
Sea cucumber (*I. badionotus*)	Same as for sand scallop	R&D for testing hatchery-based juvenile production for Bermuda species/ Investigate and implement pilot study for suspended culture technology and pond culture	Strong international market demand/ High market value supporting export market	Culture protocols not fully developed for hatchery/ Alternative (non-bottom) farming technique required for Bermuda

Table 12. Priority Level 3 species requiring further R&D for the development of scalable culture protocols.

Species	**Rationale for Level 3 prioritisation**	**Recommendations**	**Strengths**	**Weaknesses**
Turkey-wing mussel (*A. zebra*)	Complete culture cycle techniques not available/ Estimated time to market 3 years; not confirmed	Complete research programme- developing culture techniques for whole life cycle/ Investigating government-subsidised stock enhancement using hatchery-produced seed for local fishery	Locally available broodstock/ Hardy species	Low market demand (domestic and export)
Sea urchin (*T. ventricosus)*	Juvenile to market size rearing challenging/ Natural stocks unlikely to support roe-enhancing operations.	Full research programme adapting hatchery techniques for juveniles to Bermuda/ Investigating potential for new cage culture technology for sale (juvenile to market)/ Investigating government-subsidised stock enhancement programme using hatchery-based juveniles/ Financial analysis	High market value and export demand	Unknown natural stock status (Bermuda) for broodstock and/or roe-enhancement
Spiny lobster (*P. argus*)	Low survival for larval stages/ Most operations relying on collection of larvae or juveniles from the wild	Investigate partnership with new Australian-based company	Commercial hatchery-based culture techniques proprietorial	Most existing strategies unsustainable (reliance on natural juvenile collection)
Greater amberjack (*S. dumerilli*)	No commercial source of fertilised eggs/juveniles Gaps in biological requirements for juvenile production Bermuda winter temperatures may increase time to market. Growth rate decreases below 21°C; substantially reduced below 17°C.	Investigate source of fertilised eggs (European private sector/possible future source Florida)/ Research programme to adapt and develop culture techniques in Bermuda/ Comparison of growth in offshore cage system and RAS/ Investigate partnership with existing commercial operation in Hawaii (hatchery production of another *Seriola* species)	High value and high demand (sashimi quality; low wild catch supply)/ Leading finfish culture candidate in Europe; ongoing R&D efforts/ Whole cycle production demonstrated in RAS/ Existing research hatchery in Malta	Time to market long- 24-36 months minimum for 3-5kg fish.

Species cont'd	Rationale for Level 3 prioritisation	Recommendations	Strengths	Weaknesses
Seaweeds	Lack of data on natural stocks, culture requirements and environmental tolerance	R&D to develop culture techniques/ Assessment of invasive potential when cultured at scale nearshore/ Assessment of market products for selected species	Generally fast growing/ High market demand (export)/ Potential integration with finfish RAS culture	Some species reported to be invasive/ Processing costs likely to be a substantial component of operation
Sargassum sp.	Sporadic natural influx for natural collection/ Lack of data for culture protocols	Full research for hatchery-based seed production/ Investigate harvest of Sargassum washed ashore for processing and sale/ Financial analysis for processing costs	Fast growing/ Natural occurrence of large volumes available for collection	Reliance on harvest of natural populations/ Uncertain financial profitability

7. Integrating Aquaculture: Multi-species and multi-sectoral approach

Integrated Multi-Trophic Aquaculture (IMTA) is a form of polyculture using species from multiple trophic levels, which makes use of the byproducts (including wastes) from one species as inputs (such as food) for another; fed aquaculture systems are combined with extractive (or non-fed) aquaculture to create a balanced system. This is one form of management in finfish cage culture which allows for the assimilation of fish waste particulates and dissolved nutrients into additional valuable crops, thereby reducing environmental discharge and expanding the economic base of a farming operation. The species most commonly selected for IMTA with marine fish are seaweeds, oysters and mussels, but lobsters, sea urchins, sea cucumbers and others have also been considered.

Emerging studies also point to the suitability of multi-use aquaculture integrating selected species and cultivation systems with different sectors, namely the renewable energy sector (Buck *et al.,* 2017).

A simplified diagram of an IMTA farm offshore is given in Figure 11.

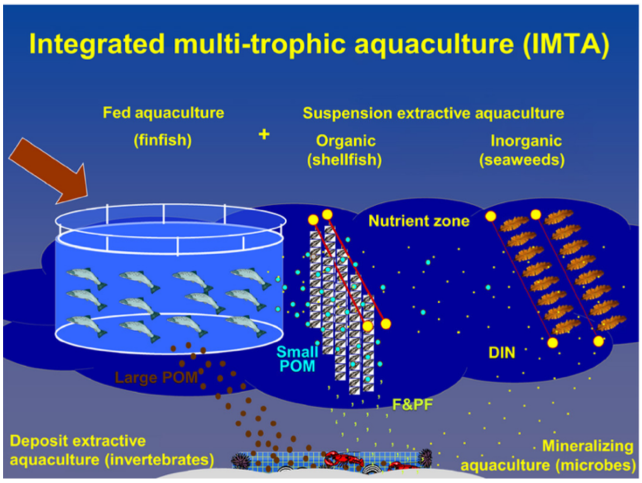

Figure 11. Simplified diagram of an offshore IMTA system, exemplifying the integrated culture of fed and non-fed species (Clements and Chopin, 2016).

Examples of IMTA systems and multi-use aquaculture are given for culture candidates listed in this document in Table 13.

Table 13. Examples of Integrated Multi-Trophic Aquaculture (IMTA) systems and cross-sectoral systems relevant to Bermuda..

Type	Species	Recommendations	Strengths	Weaknesses
IMTA	Oysters/scallops and finfish species	Research on offshore bivalve culture and effects of co-culture	Diversification of end products: bivalve (and pearl if using oysters), finfish Increased nutrient availability for bivalves Potential mitigation of finfish biodeposition impact Increased production in a given area Increased risk management strategy	No data on offshore pearl oyster or scallop culture and resulting growth, survival (and pearl formation)
IMTA	Oysters/scallops and sea cucumber	Research on increased stocking density of sea cucumber on bottom through increased nutrient deposition by bivalves	Diversification of end products: Bivalve (pearl if relevant), sea cucumber Increased ecological carrying capacity for sea cucumbers, and increased production in a given seabed area	No data on stocking densities of sea cucumbers
Co-culture	Land-based juvenile/adult finfish with seaweed (Fig. 11)*	Research on seaweed production Research on removal of nutrients and 'cleaning' of effluents from finfish nursery	Diversification of product within land-based system: finfish and seaweed Utilisation of finfish waste for land-based production of seaweed	Data required for co-culture of selected finfish species with *Agardhiella*
Cross-sectoral systems	Bivalves and offshore wind farm	Research on scallop production in wind farm environment	Reduction of costs for offshore bivalve farming	Engagement of future wind farm industry sector needed Little data available

*Current experimental work at the University of Miami (D. Benetti, *pers.comm.*)

8. Technical and Economic Constraints and Risks: Current and Future

8.1 Aquaculture in Bermuda: Constraints and Advantages

General constraints for aquaculture in Bermuda are:

- Space availability of farm sites allowing expansion of operation
- Limited sites with high food availability (for low trophic levels)
- Availability (and zoning) of land suitable to hatchery activities in proximity to a clean seawater source
- Availability of local broodstock
- Access to fertilised eggs/larvae (finfish)
- Unknown carrying capacity of natural environment
- Winter sea ambient temperatures at low range of tolerance for several marine species (reduced growth rate, increased time to market, and/or mortality)
- Sensitive ecosystems (seagrass and coral reefs)
- Vulnerability of nearshore biodiversity to small environmental fluctuations
- Limited on island knowledge of culture for native species

- Limited domestic market demand
- High production costs and challenge in being competitive at international scale
- Economic constraints for offshore culture summarised as 'economies of scale'- mainly due to high capital and operational investments

Advantages are:

- Presence of infrastructure
- High level of education and skill set- easily trainable
- Strong database and understanding of natural environmental parameters
- Demonstrated pilot scale operation for bivalves
- Access to technical support (resident and overseas)
- Clean natural seawater (hatchery and farm)
- High market value for domestic products
- Access to export market

The advantages and constraints for Bermuda point to the development of an aquaculture industry with the following characteristics:

- Application of ecosystem-based approach
- High value species
- Efficient and compact systems using advanced technology
- Reliance on technology and small staff with high skill set
- Diversification of product forms using multi-species

Future constraints in assessing and predicting the sustainability of aquaculture operations in Bermuda are similar to those worldwide, and relate to climate change. Coastal acidification has already had significant impacts on coastal aquaculture operations around the world, forcing oyster hatcheries to modify incoming seawater and in some cases to relocate. Of concern in some regions is the increased frequency of marine heatwaves defined as warm water anomalies occurring across thousands of kilometers and lasting for up to months; these cause summer mortalities and increased disease in aquaculture species. In coastal areas, acidification and warming also act synergistically with anthropogenic inputs such as eutrophication and sedimentation from increasing land use. This is mitigated in part by diversification of culturing other species, and expanding into the open ocean, which may offer some inertia to the rate of change in thermal and pH parameters, and alleviate the negative impacts especially on shellfish aquaculture. Seawater chemistry monitoring by the Bermuda Institute of Ocean Sciences provides data essential to future aquaculture operations. Some of the influences of climate change could include (1) negative effects of acidification on calcifying life stages for bivalves , (2) changes in the abundance of food sources (e.g., phytoplankton) for bivalves, (3) greater fluctuations in temperature and salinity, (4) novel disease threats, (5) increases in biosecurity incursions and/or biofouling species and (6) increases in the frequency of storm events affecting gear.

8.2 Risks in aquaculture

A full risk analysis for an aquaculture operation includes both: 1) the impact of aquaculture to the environment, and 2) the impact of the economic/social/environmental conditions to aquaculture. Hazards to and from aquaculture associated with each risk are well documented, and risks can be categorized as follows:

- Pathogen risks
- Food safety and public health risks
- Ecological (pests and invasive) risks
- Genetic risks
- Environmental risks
- Financial and social risks

Ecological, genetic, and environmental risks specific to the species prioritised here have already been discussed under environmental concerns in the relevant sections. Methodologies and risk-based policies are available for a full risk analysis and developed for most of the categories listed above; these are based on international codes such as the Aquatic Animal Health Code of the World Organisation for Animal Health for pathogen risks (OIE), or Codex Alimentarius for food safety and public health risks (FAO/WHO) (Arthur *et al.,* 2009).

The main production risk relevant to Bermuda is related to the loss of stock at farm sites due to:

a) Phytoplankton/bacterial blooms – reported occasionally to achieve substantial impact level in Bermuda's inshore bodies of water
b) Loss of gear/nets due to storms and hurricanes.
c) Loss of juveniles following transfer to farm due to predation within enclosures. This is exemplified in several case studies, when seed stock is transferred during times of crab recruitment; crabs prey on small seed. BMP and an understanding of biological characteristics of site mitigates this type of loss.

Additional risks specific to finfish in Bermuda are:

- Low acceptance of fishing industry for snapper culture- regarded as a competitive industry
- Finfish nutrient input in offshore cages trigger harmful phytoplankton bloom; this is a major unknown factor at the time of writing.

9. Recommendations and Conclusions

In order to start an aquaculture operation, a business plan including a marketing plan, and proposed Best Management Practices is required. This should be followed by:

1) Final site selection for a specific species: This should follow up on identified sites in this study with individual localised and detailed investigations with updated data given in this report.
2) An estimation of site-specific ecological, production and social carrying capacity as possible.
3) The validation of the proposed technology and carrying capacity through site-specific pilot scale or 'demonstration projects', if not previously done.

The successful implementation of a new industry and recommended BMPs require a clear policy and legislative support. Bermuda has an aquaculture policy (2011), and a regulatory framework approved by cabinet (T. Warren, *pers.comm*.). Some regulations are included in the Fisheries Act (1972).

As a potentially new industry, aquaculture faces several regulatory and management challenges. Current status in Bermuda for the start-up of an aquaculture operation requires the approval of independently managed government departments, each relevant to one component of an aquaculture operation, with limited if any precedence on level of regulation required. Relevant departments in Bermuda are:

- Department of Environment and Natural Resources
- Department of Marine & Ports
- Department of Works & Engineering
- Department of Planning
- Department of Health

In the absence of a clear process, it becomes the responsibility of the aquaculturist to provide all information, such examples of other jurisdictions for seabed lease costs, environmental impact projections, etc. This system is inefficient, drawn-out, discourages investment and does not ensure sustainability (economic, social and environmental) of the industry. The need to develop legal and institutional instruments for aquaculture is now widely recognized.

Lessons learnt from other jurisdictions (Tatoukam and Erikstein, 2013) indicate that: Primarily, aquaculture needs to be recognized as distinct from the agricultural sector, and a consistent approach to addressing issues pertaining to planning, developing, implementing and managing an aquaculture operation outlined. The design and administration of legislation should aim to ensure sustainability without the imposition of significant unnecessary costs on the aquaculturist. If well designed, a regulatory framework for a sustainable aquaculture operation provides the basis for:

- Careful planning, zoning and prioritization of sites among the different potential users
- Clear identification of national policies and procedures- this includes permitting/licensing
- Specific methods to regulate aquaculture- for example, limitations on use of non-native species, mandatory reporting of escape incidents.

This regulatory framework, or ‘Aquaculture Act’ is best managed by a stable institution set-up, preferably dedicated to the industry. Steps required to establish control over the industry can be extrapolated from other jurisdictions.

The main stumbling blocks in the development of aquaculture in Bermuda include the lack of precedence in commercial scale aquaculture, the fear of risk-taking without proof of concept, and the absence of a multi-year strategy supported by policy. Risk mitigation can be approached through diversification of products, a multi-species industry, and the identification of technical/economical source of support. A multi-annual plan for the development of the aquaculture industry based on scientific data and cultivation know-how can provide the required strategy; and the implementation of such a plan can demonstrate the proof of concept necessary for investments and for scaling production. This document is a first step in the formulation of a Bermuda strategy.

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Appendix 1: Bermuda Candidates Culture Species Fact Sheet

Potential culture candidates for Bermuda are listed based on two criteria: 1) species is native to Bermuda, and 2) culture techniques are known for the whole life cycle, or part of the life cycle. This is a simplified approach to listing, and excludes environmental, economic and social sustainability factors.

Low Trophic Level:

Twenty-two native molluscan/shellfish species have been identified as potential targets for aquaculture in the Wider Caribbean Region (Lovatelli and Sarkis, 2011) – including gastropods, crustaceans, bivalves, echinoderms and cephalopods-. The species most relevant to Bermuda are:

A. BIVALVES

The calico scallop, *Argopecten gibbus* (L.) is largely restricted to the sub-temperate and tropical waters of the western North Atlantic with major stocks distributed from Cape Hatteras, North Carolina (USA) to the Cape San Blas areas of the northeastern Gulf of Mexico (Waller, 1969). Calico scallops have also been collected from the Greater Antilles, Bermuda, and the western portions of the Gulf of Mexico (Waller, 1969). Commercially important stocks are located off North Carolina and northeastern Florida (USA), where it supports a small and transient fishery, with landings fluctuating between 550 kg/year and 19.5million kg of muscle meat/year, demonstrating a 50-fold change in abundance in local populations between successive years. The value of the fishery was recorded to peak at 23 million USD in Florida in the 1980s (Geiger *et al.,* 2015). A pilot scale aquaculture operation was conducted at the Bermuda Institute of Ocean Sciences (BIOS; 1999-2003) and provides the proof of concept and well tested technology for a scalable culture operation in Bermuda for this species; 4 inshore bodies of water were tested as grow-out (or farm) sites (Sarkis and Lovatelli, 2007). Insight into market price of whole fresh product in Bermuda was also obtained through the assessment of consumer and chef acceptance in 5 restaurants across the island, supplied over a 6 months trial period. There are no known existing commercial aquaculture operations in the Atlantic for this species at the time of writing.

The Bermuda sand scallop or zigzag scallop, *Euvola ziczac*, is distributed from Bermuda, North Carolina to Florida and Texas, the Caribbean, and south to Brazil. It can be found from 2-50 m and is usually buried in the sand. It supported an industrial trawling fishery in Brazil (Pezzuto and Borzone, 2004), with landings reaching 8,800 tonnes in 1980, 7 years after the opening of the fishery, followed by a collapse of the stock with no sign of recovery. Reaching 100 mm in shell size, it is a short-lived species, appreciated by consumers, and with a high market value. Its reproductive cycle is reported by S. Manuel (2001). Culture techniques are known for its entire life cycle, and well tested in Bermuda during the BIOS pilot scale aquaculture programme (1999-2003). It exhibits rapid growth, but is known to suffer high mortality rates during early life stage culture. The difference in cultivation technology with *A. gibbus* and *N. nodosus* is the reliance on bottom culture for production of market size animals, associated with its recessing behaviour (Sarkis and Lovatelli, 2007). Large scale farming for this species is not reported at the time of writing.

The lion's paw scallop, *Nodipecten nodosus,* is one of the largest scallop species in the Wider Caribbean and reaches 150 mm in shell length. It inhabits the sub-tropical and tropical waters of the Atlantic Ocean, with known habitat ranging from North Carolina, Florida and Texas, extending to Bermuda, south to Brazil and eastward to Ascension Island; it is found in deeper waters, 9-49 m (Abbott and Morris, 1995). Its occurrence in Bermuda is based on empty shell collection from deep waters (Smith, 1991); current status of live populations in and around Bermuda are unknown. Commercial culture is practiced in Brazil, with a reported production of 20 tonnes in 2009 (Abelin *et al.,* 2016). Culture techniques are well tested for all life stages.

The pearl oyster, *Pinctada imbricata,* is widely distributed in the Caribbean Region, ranging from Bermuda, North Carolina (USA) to Brazil (Carpenter, 2002). The species is very abundant on the northeastern coast of South America forming dense banks in the Caribbean Sea, and commonly seen in Bermuda. A hardy species, it takes 12-18 months to reach 55-65mm; meat weight is relatively low (20g). Harvest of adults for meat is recorded at a maximum of 71 tonnes in the Caribbean (2008) (Lovatelli and Sarkis, 2011). Large scale pearl culture techniques for other *Pinctada* species are well established, with leading producers being Japan, China and French Polynesia; total marine pearl production is reported at 54.5 tons per annum (Zhu *et al.,* 2018). *Pinctada imbricata fucata*, closely related to the Bermuda *Pinctada imbricata radiata,* is commercially farmed for Akoya pearl in Australia since 2003 (Otter *et al.,* 2017).

Turkey-wing mussel, *Arca zebra*, is an ark shell up to 100m shell length. It occurs naturally from North Carolina to Florida and Texas (USA), Bermuda, in the Caribbean, and south to Brazil. It supports artisanal fisheries of socio-economic importance in the southern part of its range (e.g. Bolivia and Venezuela). Harvest is recorded to range between 5,792 to 33,986 tons per year and peaked at 40,000 tons in Venezuela (Peralta *et al.*, 2016). *A. zebra* is most likely one of the most abundant bivalve species in Bermuda and is found from intertidal zone to depths of 27 m. The majority of individuals occur in patchy beds on the North Shore of the island (10-14m) and in several of the inshore waters, namely Harrington Sound with recorded densities of up to 59 mussels/m^2 (Sarkis, 1992; Pitt and Hallett, 2012). Research on its natural reproductive cycle and larval phase has been conducted in Bermuda, and culture techniques are believed to be similar to those of other mussel species. There are no existing known pilot scale or commercial operations.

B. ECHINODERMS

Four-sided sea cucumber, *Isostichopus badionotus*, is one of the most highly valued commercial species of sea cucumbers in the Wider Caribbean Region. It is widely distributed throughout the Region extending north to Bermuda, through the Caribbean Sea, the Gulf of Mexico and to the Caribbean coast of Bolivia and Colombia (Lovatelli and Sarkis, 2011). In Bermuda, the species is found on sandy bottoms in the inshore waters to depth of 10 m. Increasing interest in this species globally and in the Caribbean, is due to the high market price value (132–358 US$/kg) driven by the Chinese and southeast Asian demand (Purcell *et al.,* 2018). Cuba and Mexico have regulated fishing activities on *Isostichopus* species; Panama, Bolivia, Venezuela and the Dominican Republic also have records of intense fishing activity. FAO records for the Cuban fishery indicate a decline in harvest from 3 million to <500,000 over a 4-year period, reflecting overexploitation. Some Bermuda data on natural spawning period is available through citizen science efforts (D. O'SheaMeyer, *pers.comm.*). Preliminary research indicates the presence of anti-cancer properties in *I. badionotus* of benefit to medical research (Sarkis, 2014; unpub.). Culture techniques are well established for more temperate species; preliminary trials for hatchery production of *I. badionotus* juveniles in Bermuda proved promising (Sarkis, 2014; *unpub.*); sea cucumber larval rearing has similar facility requirements to those for bivalves.

The sea egg urchin, *Tripneustes ventricosus*, is widely distributed extending from the Carolinas and Bermuda, to Florida, across the Caribbean Sea, to Belize, Venezuela, and southerly to Brazil. It is common in shallow coastal waters. The species supports small-scale, commercially important, seasonal fisheries in several islands in the Lesser Antilles for local consumption, FAO statistics report 10 tonnes of harvest per year for Martinique (Lovatelli and Sarkis, 2011). The roe or 'uni' is highly valued in the Asian market, and several countries put much effort in reseeding harvested sites or in roe-enhancing of harvested adults (*Strongylocentrotus sp.* in Canada, Norway). There is no commercial culture operation for this species in the Latin American and Caribbean Region. Techniques for early life stages, up to seed production, are well tested for *Tripneustes* species (Creswell, 2011). Grow-out of sea urchin seed to market size is for the most part sea ranching (seeding juveniles on seabed), and conducted for stock enhancement (Creswell, 2011), or as biological control agents reducing impact of invasive seaweed (Neilson *et al.*, 2018). New patented technology relying on nested inter-locking crates is tested in Norway for juvenile rearing in suspended cultures (James *et al.,* 2020); note that using this system becomes similar to a higher trophic level operation, as sea urchins are fed a manufactured diet weekly.

C. GASTROPODS

The Queen conch, *Lobatus (Strombus) gigas*, lives on sand near seagrass beds at depths of 2-30 m, and occurs naturally in Bermuda, southeastern Florida (USA), the Caribbean, Mexico, and Brazil (Lovatelli and Sarkis, 2011). Due to exploitation, stocks are severely depleted throughout most of its range, and it is listed in Appendix 2 of CITES. In Bermuda, queen conch breeding areas have been recorded in 3 specific sites at approximately 7-10m depth – North Rock, Castle Roads and Hogfish Cut (Sarkis and Ward, 2009). The Queen conch supports an economically important fishery (domestic and export) in the Turks and Caicos Islands (Rudd, 2003). Commercial culture was practiced for several years in the Turks and Caicos Islands (TCI), and currently in Puerto Rico, relying on the collection of egg masses from the natural stocks (Davis and Cassar, 2020). A 2-year old product was marketed by TCI conch farms with some success. Culture techniques are well developed and tested in the Caribbean, including hatchery phase and grow-out in land-based ponds and shallow water bottom enclosures.

D. SEAWEED

Seaweed farming is increasingly considered as a promising source for food, feed and biobased economy[3]. Algae (or seaweeds) serve as a source of raw materials for stabilizers or thickening and gelling agents, such as agar, alginate, and carrageenan. Research is also increasingly active in assessing their potential as a carbohydrate source for bioplastic development. These are not only biodegradable, but their properties can also help to extend the shelf life of food products packaged in them. One of the main advantages to seaweed culture is their fast growth rate. However, this has also

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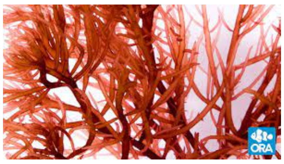
[3] Biobased economy- An economic activity involving the use of biotechnology and biomass in the production of goods, services, or energy

led to the invasive nature of seaweed culture reported for several species- namely *Euchema sp.*- Some information relevant to their aquaculture potential is given in DeBoer (1983). Species native to Bermuda and potentially of interest for commercial culture are given below; minimal information is available (DeBoer, 1983).

Caulerpa racemose

Hypnea musciformis

Agardhiella floridana



Agardhiella ramossisima

Eucheuma isiforme is closely related to *Eucheuma* species harvested in Antigua, Anegada (BVI), Barbuda, Barbados, Belize, Jamaica, St. Lucia, Trinidad and other countries where the plants are used to make a “sea moss” drink or pudding (DeBoer, 1981). *Euchema sp.* (or Kappa) is one of the most valuable tropical red algae species, with a global production of 120,000 dry tons/year, coming from Asia and Africa. Culture techniques for Kappa are well developed and tested (McHugh, 2003). Hawaii practises pond culture, and has reported this species as an invasive to Hawaiian waters (DLNR, 2021). Current efforts in the Caribbean to develop *E. isiforme* commercial culture are conducted by the Marine Biological laboratory (University of Chicago) in collaboration with The Nature Conservancy (*mbl.edu/tropical-seaweed/*).

Sargassum sp., a free floating brown macroalgae is found in the Atlantic Region. It is a source of chemical compounds with a wide range of applications in the pharamaceutical, biomedical, dental, textile and printing industries, as well as a source of raw materials for extracting natural fertilizer and biostimulants. *Sargassum* has also been found to have biosorptive capacity that has the potential to recover chemical pollutants and be reintegrated into the value chain. It is harvested from the wild, or gathered once washed ashore. Demand for Sargassum raw materials is growing for foreign markets, such as China, Japan and Korea. Culture methods have been developed for several species, where seedlings are produced in hatcheries and transferred to a sea-based farm (Largo *et al.,* 2020). In the Caribbean, new companies are harvesting Sargassum for skin care products and fertiliser. The global sodium alginate market (one of the main properties of Sargassum) is estimated at $624 million/year (McHugh, 2003). High fluxes of sargassum washing ashore the Caribbean Region have led to negative socio-economic impacts on the fishery sector (Ramlogan *et al.,* 2017); alternative management strategies are leading to new initiatives relying on natural collection and making use of the natural properties of this species.

E. CRUSTACEAN

The Caribbean spiny lobster, *Panularis argus*, occurs naturally in Bermuda, North Carolina (USA), southward through the Gulf of Mexico, Antilles, and the coasts of Central and South America to Brazil (Lovatelli and Sarkis, 2011). It lives in shallow water to 90 m; it is associated with coral reefs, in seagrass beds as juveniles or any other habitat affording shelter. It is the most economically important fishery product in the Caribbean Region, landing up to 40,000 metric tonnes, with an annual value ranging from US$ 400 million to US$1 billion (Davis *et al.,* 2007; WECAFC, 2018). Of the dozen species of tropical lobsters around the world, the available aquaculture information and strongest interest focuses on *P. argus*. Spiny lobster has expanded rapidly in Southeast Asia, and relies on collection of juveniles from natural stocks. Similarly, a commercial operation reports the collection of lobster larvae for grow-out in land-based nursery and farming in floating cages in the British Virgin Islands (Caribbean Sustainable Fisheries). Experimental culture techniques for hatchery production of juveniles are successful and enhance natural larval growth rate, substantially reducing time in captivity from 9 months to 2 months (D. Fletcher, *pers.comm.*). A first commercial hatchery has completed construction in Australia (2020), with the goal of producing 1000 tons per annum. Commercial culture techniques are highly proprietorial and not easily accessible.

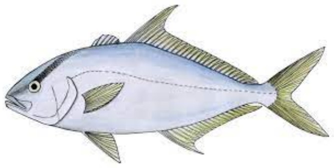
High Trophic Level:

Finfish culture was flagged as a priority by the Bermuda government. Applying the same criteria as for low trophic levels (native, known culture technology), results in the listing of 5 species.

A. FINFISH

The mutton snapper, *Lutjanus analis*, occurs in the western Atlantic Ocean from Massachussets to Brazil, Bermuda, Gulf of Mexico and is most common in tropical waters of Florida, the Bahamas, and the Caribbean Sea. Mutton Snapper is reported to have been introduced to Bermuda in the 1920s (Randall, 1996); currently, it is considered rare in Bermuda (DENR, *pers.comm.*). Large adults are usually found in or near offshore reefs, at depths of 25-95 m. There are no specific record for mutton snapper landings in Bermuda, but all snapper landings (reporting 5 species of snappers) average 37,700 kg/year over 5 year period (2012-2017) (DENR, 2021). Mutton snapper culture techniques are well developed (Watanabe, 2001); commercial production is ongoing in Florida, using recirculating aquaculture systems (RAS) for juvenile production and cage culture for market size, with offshore sites previously tested in Puerto Rico (Benetti *et al.,* 2007).

The lane (silk) snapper, *Lutjanus synagris*, is found in the western Atlantic Ocean, from North Carolina to southern Brazil. It is most abundant in the Antilles, off Panama, and the northern coast of South America. It also occurs in Bermuda and the Gulf of Mexico. This species supports important fisheries in Florida, across the Caribbean and Bermuda. Landings in Bermuda, average 15,073 kg/annum (1975-2017) (DENR, 2021). Commercial landings of snapper (Lutjanidae- including lane snapper and other species) in the southeastern U.S. approximate 4,832 metric tons with a dockside value of $10,365,000. Culture techniques are similar to mutton snapper and also ongoing in Florida for large scale juvenile production using RAS technology (D. Benetti, *pers.comm.*)



The great amberjack, *Seriola dumerili,* (top) and almaco jack, *Seriola rivoliana*, (bottom) have a wide distribution and found in subtropical and tropical regions throughout the Atlantic and Pacific Oceans. In the western Atlantic, they occur from Nova Scotia to Brazil, including the Gulf of Mexico, Bermuda and the Caribbean. *S. dumerili* is a valuable commercial species, with a limited worldwide catch approximating 3,300 tonnes in 2009. Landings in Bermuda average 8,553 kg/annum between 2012 and 2017 (DENR, 2021). *S. rivoliana* landings in Bermuda are higher, averaging 18,919 kg/annum during the same period (DENR, 2021). Aquaculture is conducted commercially for several *Seriola sp*., including *S. rivoliana*, with the majority relying on catch of juveniles from the natural stocks. The largest producer is

Japan (mainly *Seriola quinqueradiata*, known as Kampachi, with 30% of production consisting of *S. rivoliana*), maintaining a production close to 170,000 tonnes/year since 1995, despite falls in the number of wild caught juveniles (FAO, 2021). Hatchery-based production of *S. rivoliana* is currently ongoing for commercial scale farming in Hawaii (Blue Mariculture, *pers.comm.). S. dumerili* is now considered as one of the most important species to diversify the commercial production of fish in countries around the Mediterranean and in North and South America, and experimental work on hatchery-based juvenile production is intensifying (Papandroulakis, 2018).

The cobia, *Rachycentron canadum*, is found in warm-temperate to tropical waters of the West and East Atlantic Ocean, throughout the Caribbean, and in the Indian Ocean off the coast of India, Australia, and off the Pacific coast of Japan. It does not support a fishery, but is considered one of the most suitable candidates for warm open-water marine aquaculture in the world (FAO, 2021). Cobia is cultured in nurseries and offshore cages in parts of Asia, the United States, Mexico, and Panama. Commercial scale culture of egg production is conducted in Florida (University of Miami) and Texas (University of Texas Marine Science Institute) to support operations worldwide. World aquaculture production for this species exceeds 43,000 metric tonnes, with 80% produced by China and Taiwan using cage culture (FAO, 2021).

Appendix II: Scallops - Environmental Concerns

FEED

Hatchery- scallops and oysters are fed phytoplankton, reared in closed vessels, with nil to negligible input into the surrounding water. Overfeeding is detrimental to larval and post-larval growth, such that aquaculturists strive to provide algae in such quantities that it is 100% cleared by cultured species, with near zero input of leftover feed in effluent water.
Farm- scallops and oysters feed on phytoplankton and other particulate matter available in the environment. There are no concerns with respect to the input of feed in farm sites.

GENETIC IMPACT ON WILD STOCK

Farm- There is a lack of data globally regarding bivalve genetics, breeding, and genomics, making it difficult to assess the impact of cultured stocks on wild stocks; of concern is the interbreeding between cultured and wild genotypes, jeopardizing wild populations by decreasing their adaptive potential. This type of interaction can only be achieved through successful large-scale settlement of cultured stocks in the surrounding ecosystem, following natural spawning events. However, natural survival rates of larvae and recruited spat are low, subjected to high mortalities due to predation. This explains to some extent, observations made during and following a 5-year pilot scale operation in Bermuda, where there was no marked increase of natural calico scallop population (Sarkis, *unpub.*); this implies a low impact of scallops recruited from culture operations to the natural environment. The observed low population levels for both scallop species in Bermuda suggests that any genetic impact on the existing wild stock may be a positive factor, enhancing natural stocks. In order to avoid long term inbreeding depression, Best Management Practice (BMP) calls for diversification of broodstock for culture, to ensure genetic diversity (Appendix V). Data on existing population levels in Bermuda should be updated.

SOURCE OF STOCK

Hatchery- In most countries, scallops for broodstock are usually selected from wild stocks. Despite this partial dependence on wild stock for broodstock, the removal of the necessary number of scallops from the wild typically does not have negative impacts on wild stocks (Heinonen, 2013) However, if surveys on Bermuda scallop populations confirm low levels, broodstock for each species will need to be imported. BMP calls for procedures to ensure that imported animals are maintained under quarantine conditions, in a closed system preventing pathogen entry into the natural environment. BMP also calls for the transfer of F1 generation spat and subsequent generations to farm sites for grow-out to market size; holding of imported broodstock in farm sites should not be allowed (Creswell and McNevin, 2008; Appendix V). Such protocols exist and have been tested as successful biosecurity measures.

EFFLUENTS AND WASTE DISCHARGE

Hatchery effluents- There has been little discussion regarding effluents from shellfish hatcheries, largely due to the fact that no drugs, pesticides, or herbicides are added to the seawater that flows through and around the shellfish. Bivalves sequester bacteria and phytoplankton from the surrounding water, and essentially cause the hatchery effluent to be cleaner than the water that entered (Heinonen, 2013). For this reason, several states within the U.S. do not require discharge permits (EPA online, Additionally, the National Pollutant Discharge Elimination System has an exemption for hatcheries that produce less than a specified number of pounds of animals. Land-based nurseries pump ambient seawater to the facility and may require a discharge permit solely for this reason.

Hatchery wate discharge- Discharge is in the form of faeces and pseudofaeces, with most originating from broodstock; broodstock can be held in sand-filtered tanks, where most of the faeces is retained. Regarding land-based nurseries, faecal discharge from spat/young juveniles is minimal, and if the nursery is located in an area of high flushing, impact should be minimal. However, discharged water should be monitored routinely as a BMP.

Farm waste discharge: Organic biodeposition for bivalves is flagged as a concern if carrying capacity is exceeded and in areas of low flushing. However, it is widely recognized that effects of scallop culture are insignificant relative to other forms of culture because artificial feeds are not used (Giles *et al.,* 2009). Bivalve species differ in the amount of organic materials deposited, with scallops at the lower end of the spectrum and oysters at the higher end. Estimated carrying capacity for a given site is species specific. While the accumulation of biodeposits usually results in increased nitrogen and reduced oxygen concentrations, the general belief is that if the carrying capacity is not exceeded, the benefits of scallop culture far outweigh the minimal costs.

ANTIBIOTICS

Hatchery- The amount of chemicals used in scallop hatcheries is negligible if at all; generally, when needed antibiotics are utilised during monitoring of larval cultures and administered in a static tank for a short period of time (Sarkis and Lovatelli, 2007). Water discharged should be free of antibiotic, if proper dosage is applied. Thus, there is no threat of chemical contamination of adjacent waters. Generally, there is no use of chemicals during the nursery phase, and none in any flow-through systems; as most hatcheries are moving towards flow-through systems for both larvae and spat, the use of antibiotics is decreasing. In addition, current efforts are made to routinely introduce probiotic bacteria to bivalve hatcheries and nurseries, as a substitute to antibiotics; these protocols are not yet well established for all bivalve operations.

Farm- There is no use of chemicals for health treatment or fouling control. Fouling control is most effective through manual removal, and does not entail discharge of active chemicals.

ESCAPE RISK

Farm-The risk of escape is directly related to degree of connection to the natural ecosystem. For farmed scallops, the intermediate (nursery) and grow-out phase are the two most relevant. There is little chance of escape from farm sites since nets or mesh are generally used to secure the scallops. For this reason, even though scallops are farmed in open systems, the risk criterion does not directly apply in this case. Larval distribution following spawning is considered unlikely as an escape risk due to the high natural mortality incurred.

INTRODUCTION OF ALIEN SPECIES

Hatchery- This concern is relevant mainly if broodstock are imported from overseas, especially if they are sourced directly from wild stocks in the country of origin. Scallops are shipped in insulated containers, and kept moist through the use of materials. There is no water associated with transport, and the risk of introduction of alien species is minimal, if broodstock is shipped according to BMP.

DISEASE INTERACTIONS

Farm- Relatively few diseases have been reported in scallops (Heinonen, 2013). Disease interactions are usually related to the impact of the environment on the farmed stock, rather than that of aquaculture on the environment.

IMPACT ON HABITAT AND BENTHOS

Farm- Degradation to habitats occurs mainly where harvesting is conducted by dredge. This is mitigated by appropriate site selection at distance from seagrass or coral reefs. Anchor damage is associated with one fixed point at time of longline installation, and generally considered negligible. Effects to habitat function and services from scallop culture are expected to be minimal.

Overall, scallop aquaculture is considered relatively low environmental impact, and Monterey's Seafood Watch classified scallops cultured in suspension as Best Choice (Heinonen, 2013).

Appendix III: Oysters – Environmental Concerns

The following environmental concerns are not of concern in oyster production for the same reasons as given for scallops:

- Feed
- Hatchery effluents
- Antibiotics
- Escape risk
- Introduction of alien species
- Disease interactions

Issues of concern in oyster farming are given below, with one additional concern to that of scallop culture, labelled as 'competition for food'.

SOURCE OF STOCK

Hatchery- Pearl oysters are at the time of writing observed to be relatively common in Bermuda, and it is anticipated that a broodstock can be collected from natural populations. In this case, there is no cause for concern.

COMPETITION FOR FOOD

Farm- This is one of the greatest potential impacts of oyster farming (Oo and Oo, 2016). The high filter feeding rates by oysters have a greater effect on the removal of phytoplankton from the water (compared to scallops), and in this way exert control on phytoplankton growth, potentially affecting other naturally occurring filter feeding organisms. Oysters also consume detritus and can thus have an impact on its abundance and composition in the water. Both of these potential impacts depend on the volume of oysters cultured, and the extent to which this competition for food would impact wild stocks of molluscs in Harrington Sound and Castle Harbour is uncertain. In addition, the current status of natural population levels for other molluscs in Harrington Sound and Castle Harbour is not available.

WASTE DISCHARGE

Farm- The accumulation of faeces and pseudo-faeces under the oysters' beds, is referred to as biodeposition, and associated with the high filtration rate characterising oysters. Organic enrichment is recorded at some farm sites, especially beneath intertidal or off bottom oyster racks; in these sites biodeposition leads to increased sedimentation of both organic matter and contaminants beneath the racks. Proposed cultivation technology for Bermuda is suspended cultures, which mitigates waste discharge at farm sites via a greater dispersion potential, especially in areas with high local flushing rates (Turner *et al.,* 2019).

DISEASE INTERACTION

Farm- Models demonstrate that open-water oyster aquaculture will reduce disease in sympatric populations when cultured populations deter disease agents from infecting hosts in the wild, either by serving as incompetent decoys for parasite stages, or, when serving as hosts themselves so long as they are harvested before disease peaks. Similar to scallops, it is the impact of the environment on the cultured stock which is of concern; through suspension feeding, oysters are exposed to the water-borne stages of disease-causing parasites, including the agent of dermo disease, *Perkinsus sp.* It is not harmful to humans, but has resulted in heavy losses in oysters of the genus *Crassostrea* (Smolowitz, 2013), and is reported in some *Pinctada* species; levels of infestation range from minimal compared to other bivalve species sampled from the same body of water (Humphrey, 2008), to high and a potential major cause of the observed decline of pearl oyster populations (Sanil *et al.,* 2010). Infections with *Vibrio sp.* have also been reported to invade mature pearl oysters and associated with mortalities; stress, including reduced temperatures during post-transport (from nursery to farm), and low salinity are identified as playing a major role in such infections (Humphrey *et al.,* 1998).

Mitigation is through Best Practice Management of oyster farming (transport protocols, handling and controlling densities) (Appendix V).

IMPACT ON BENTHOS

Farm- Shading by high density oyster enclosures may have a detrimental impact on benthos such as the seagrass beds (Oo and Oo, 2016). This is mitigated by appropriate site selection at distance from seagrass or coral reefs; preferred bottom type is soft bottom (sandy or sediment), such as that of sites in Castle Harbour and Harrington Sound (Fig. 5). Potential impact from farm activities and anchor damage is assessed as for scallops (Appendix II).

POSITIVE IMPACT OF OYSTER FARMING

Farm- Two potential positive impacts of oysters on the surrounding environment are identified here, resulting from oyster biodeposition and oyster filtration rates. 1) Oyster biodeposits are rich in nitrogen and phosphorus and may represent a significant proportion of the energy potentially available to consumer invertebrates as a food resource. In this way, oysters may stimulate primary productivity, by exerting control over the amount of available mineral nitrogen and phosphorus to phytoplankton. 2) Estimates filtration rates for *Pinctada* species is 25 liters/g dry tissue wt/day, and leads to the effective removal of nutrient overload in the environment- as well as to the rapid bioaccumulation of heavy metals and organic pollutants (Gifford *et al.,* 2004); these authors propose the use of pearl oyster farming as a bioremediation technology for impacted sites to remove toxic contaminants, reduce nutrient loads and lower concentrations of microbial pathogens is proposed. The accumulation of pollutants in Bermuda species, the turkey wing mussel *A. zebra*, and calico scallop *A. gibbus* associated with the dump in Castle Harbour has been studied (Flood *et al.,* 2005; Quinn *et al.,* 2005); further research is required to assess bioaccumulation by the native pearl oyster, *P. imbricata*, and the potential for this type of restorative aquaculture in Bermuda waters, with the end product being pearls rather than meat.

Appendix IV: Offshore finfish culture – Environmental concerns

FEED

Hatchery and Farm- Feed Conversion Ratios (FCR) for fish are high, indicating the need for a substantial volume of feed, averaging 2 kg of feed for every 1 kg of fish produced. Feed consists of raw fish and/or formulated feeds made of fishmeal and fish oil; both sources come from what is considered 'trash fish' (sardine, anchovy, chub mackerel, etc.) collectively referred to as the clupeiforms (Sims, 2013). These fish usually form the first step in the ocean food chain beyond primary production. Their use in finfish culture is considered a valid use of a natural, sustainable, renewable resource, so long as the fishery from where the fishmeal and fish are sourced is responsibly managed. Although stocks such as the Peruvian anchoveta fishery are sustainable in the sense that they are very well managed, they are not scalable (Sims, 2013). Best management practice warrants the development and shift towards alternative feeds with more sustainable sources (Appendix V).

GENETIC IMPACT ON WILD STOCK

Farm- Escaped fish interactions are a greater concern when non-native species are cultured. There is concern on the genetic impact of escapees from large scale fish culture on the local stocks; this depends on the local population integrity and response to local selection pressures. Many of the issues reported in the literature are associated with salmonids, and there is limited knowledge for marine fish (Bekkevold *et al.,* 2006). A major factor in the extent to which genetic make-up of wild stocks can be affected by farmed fish is the level of genetic differentiation among wild stock populations; a wild stock with a broad distribution rarely has the same genetic makeup over its entire range, and this reduces the concern of genetic make-up change through escaped cultured fish. In addition, survival rate of escaped fish is reported to be extremely low, as they are subject to heavy predation pressure by predators such as dolphins and/or sharks found in the vicinity of cages (Sims, 2013). Potential impact can be mitigated through aquaculture management by maintaining a wider gene pool among cultured stock (Appendix V); this is also beneficial to the aquaculturists as genetic variation is considered an advantage which permits flexibility and survival of a population.

INTERACTIONS WITH WILD FISH

Farm- Offshore finfish culture operations are reported to have an aggregative impact on some species of fish in the area, but this is considered neither deleterious nor significant (Sims, 2013). Fish are attracted to the site for a number of possible reasons: the fouling on the net pen, the occasional release of small quantities of uneaten food from the net pen during periods of strong currents, and the aggregative nature of objects in open water (as for fish aggregation devices). The make-up of the resident and transient fish communities around the net pens may vary over time. Barracuda, tuna, rainbow runners, wahoo, sharks and dolphins are all reported around cage culture of finfish in Hawaii. Dependent on proximity to shore, smaller reef fish are also seen around cages (sergeant majors, chromids, wrasses) (Sims, 2013).

SOURCE OF STOCK

Hatchery- Collection of locally available natural broodstock is only of concern for species with low population levels. Lane snapper and almaco jack are considered common in Bermuda, based on commercial fish landings, and should not impact natural populations. Import of fertilised eggs from a certified hatchery conducted routinely needs to consider the maintenance of wide genetic diversity in imported stock (Appendix V).

EFFLUENTS

Hatchery- If poorly managed, fish hatchery effluents could release large volumes of poor water quality, including heterotrophic bacteria and other pathogens; however, the potential impact to surface water quality from these effluents is largely unknown, and needs to be determined according to site. BMP and regulations are used worldwide to reduce these inputs; these include solid filtration and disinfection of hatchery effluents (Masters *et al.,* 2008).

WASTE DISCHARGE

Hatchery- Commercial fish hatchery generates organic and inorganic waste from uneaten food and fish faeces. Other wastes from finfish hatcheries include: fish mortalities, fish carcasses from spawning operation, sand, silt and debris settled out of facilities source water (Lalonde *et al.,* 2014). Standard methods are used to treat wastes and effectively reduce the negative impact on the environment, such as eutrophication; these incur additional production costs. Alternatively, various strategies are used, aiming to reduce the amount of solid wastes produced, and increase the efficiency of their removal, through manipulation of diet (Keramat, 2011).

Farm- Undoubtedly, the release of large amounts of nutrients – through excess feed, faecal and pseudofaecal deposition- into the marine ecosystem is the single largest concern for cage-based finfish culture. On average, the production of finfish (and crustaceans) results in a net nutrient loading; this can lead to an increase in nitrogen (N) and phosphorous (P) input, and an over enrichment of nutrients, which in turn entrains:

- Stimulation of phytoplankton blooms detrimental to ecosystem
- Harmful algal bloom
- Effects of blooms on outbreaks of cnidarians or other less desirable species
- Imbalance of nutrients at lower trophic levels (e.g. silica remains at natural levels)

Nutrient influx and subsequent impact from commercial scale operations (nearshore and offshore) have been the subject of several case studies. Most relevant is the in-depth analysis of nutrient input by a commercial scale cobia farm; cage culture details specific to this study are given in Table 14 (Welch *et al*., 2018). Data shows that although the signature of the aquaculture effluent (notably carbon and nitrogen levels) is seen immediately downstream of cages, the net effect of nutrients emitted by cage culture is minimal over a 14-month period – with no difference in chl a (reflecting phytoplankton production), undetectable ammonia upstream and downstream, and no evidence of reduced dissolved oxygen concentration around the cages. This study is in accordance with results from other offshore cases, where dispersion is such that it proves difficult to determine any measurable effect on the pelagic environment associated with nutrient influx, but also turbidity and dissolved oxygen fluxes at distances beyond a few meters of cage rims (Price and Morris, 2013). These studies confirm the benefits of shifting finfish cage culture to offshore areas characterised by high currents, to mitigate the impacts of the culture system.

Table 14. Cage culture characteristics for offshore commercial culture nutrient analysis (Welch et al., 2018).

SPECIES	**COBIA**
Distance from shore	13 km
Depth	80 m
Current velocity	0.5-1.3 knots
No. Of cages	22
Size of cages	6400 m^3
Yearly production	1,400 mt/year
Species characteristics	High FCR; high rates of N excretion; high rate of Oxygen consumption

ANTIBIOTIC USE

Hatchery- In the US, any therapeutant use is conducted under the oversight of the US Fish and Wildlife service (Takoukam and Erikstein, 2013). Juvenile fish are often vaccinated or administered medicated feed before transfer to the farm to prevent infection following stress of transfer offshore. This is conducted in a controlled land-based facility, and accompanied by water quality monitoring. Administering by immersion, results in release of larger amounts of antibiotics into natural waters, reportedly as high as 75-99% (Price and Morris, 2013).

Farm- High productivity in finfish farming is achieved by intensive farming, i.e., huge biomass grown at high densities of fish per unit of water volume; this has resulted in an increased susceptibility of fish to diseases caused by viruses, bacteria, fungi, and parasites, and the substantial use of chemicals, mainly antibiotics, for treatment. Problems and concerns are due to the development and dissemination of bacterial resistance, food safety hazards and environmental issues. This is especially true for salmon aquaculture. There is an increasing shift to the use of methods other than antibiotics for controlling pests, diseases and pathogens in farmed fish, including the recent application of probiotics. In general, improved husbandry in marine cage culture over the last 10-20 years has resulted in a tremendous decline in the use of antibiotics in several countries; however, Price and Morris (2013) indicate that antibiotics are infrequently used in US marine fish farms, in part because only three antibiotics are approved for use in the US. Application in marine aquaculture requires extra-label approval by a licensed veterinarian or under an investigational new animal drug (INAD) approval through the FDA, generally with direct oversight by a veterinarian. Any antibiotics administered but not assimilated by the fish are released into the environment where they either become dissolved in the water column or settle to the sea floor and accumulate in the sediment; residence time in the marine sediment is dependent on the antibiotic, and on the geophysical properties of the water or sediment. Environmental impacts of antibiotics may be minimized at offshore sites through dilution (Price and Morris, 2013). Additional farm BMP includes the removal of infected fish from cage cultures to avoid proliferation (Appendix V).

ESCAPE RISK

Farm- Escape problems are caused by technical and operational failures of fish farming equipment, with fish escaping through holes in the nets. Different species will behave differently in cages, and percentage of fish reported to escape varies greatly among species. Escape of juveniles and adults from poorly managed cages can be substantial; Norway reports an average of 436,000 salmon escapes /year between 2001 and 2009 (Jensen *et al.,* 2010). There are no records of escapes for snappers and amberjack, and the potential impact is uncertain. In addition to escaping as juveniles or adults, some species may reproduce in sea-cages, and thus fertilised eggs escape to the environment. The ecological effects of ‘escape through spawning’ are unclear. BMP such as improved net material for the targeted species reduce the chance of escapism (Appendix V).

INTRODUCTION OF ALIEN SPECIES

Hatchery- This is of concern for operations relying on regular movement of fish, mainly for transport of juveniles between aquaculture operations in different sites or countries. It has resulted in a number of pathogens for greater amberjack culture stocks in the Mediterranean (*S. dumerili*) (Papandroulakis, 2018). The import of fertilised eggs as a source of juveniles requires regulations ensuring certification of health from source hatcheries. BMP in the hatchery is similar to that described for source of stock above (Appendix V).

DISEASE INTERACTIONS

Farm- Much of the concern over proliferative capacities for fish farm pests, parasites or pathogens is derived from conflicts between salmon farming and wild salmon runs. For broadcast spawners and pelagic fish where there is no vulnerable migratory pattern, the risk of disease interaction is much reduced compared to the salmon. However, cultured organisms are more subject to diseases than wild stock due to high intensity rearing. The proliferation of the skin fluke, *Neobenedenia sp.,* has not been observed to be problematic in almaco jack cage-culture operations (Sims, 2013). BMP measures are usually applied by aquaculturists as it is to their benefit to actively minimise pest proliferation.

IMPACT TO HABITAT AND BENTHOS

Farm- Physical impact during the installation of cages and grid system secured by anchors will occur, and is a one-time impact as described for bivalves (Appendix II); the extent of impact depends on the number of cages, and seabed characteristics, and is minimised using appropriate site selection criteria.

ENTANGLEMENT

Farm- The interactions of marine mammals with marine fish cages and efforts to minimize potential problems are recognized, but there is little recent published, peer-reviewed literature that specifically addresses the issue. The most damaging marine mammal interactions are with pinnipeds while dolphins, porpoises and whales are viewed as a minor threat to fish cages (Price and Morris, 2013). There is no record of any US offshore farm operation of entanglement of humpback whales. There is no definitive pattern of whale avoiding or being attracted to the area (Sims, 2013). Similarly, little is known about how sea turtles may be impacted by these facilities, and the primary concern is entanglement. This risk is minimized by siting farms in areas away from known migration routes, using rigid net materials or secondary rigid antipredator nets, and keeping mooring lines taut (Appendix V).

Appendix V: Best Management Practices- Guidelines for Level 1 species

Risks to and from aquaculture operations can be mitigated to a certain extent by Best Management Practice (BMP). BMPs are a set of voluntary procedures to address areas where attention should be focused to improve production while preserving the environment. To be considered best practice, an action must maintain or increase production while minimising impact on the environment, and demonstrate the best available approach to management. Best practice depends on site-specific considerations, economic opportunities, and environmental considerations. In some jurisdictions, BMPs have become regulatory in nature, and in this case, the regulatory authorities under which the aquaculturists must conduct their operation need to be identified. For the most part, BMPs describe general principles, concepts, applications and considerations to enhance the sustainability of the individual aquaculture producers, the industry as a whole, and the environment in which it operates. They highlight best approach on all aspects, from authorisation process to contingency planning and decommissioning of aquaculture activities if ceased. The Code of Conduct for Responsible Fisheries and Aquaculture (FAO, United Nations) is a widely used baseline for international standards; it applies the precautionary approach to aquaculture while recognizing its importance, and takes into account the biological characteristics of the resources, their environment and the interests of consumers and other users. There are several certifications developed to encourage good aquaculture practice; ASC certification programme, and BAP certification by the Global Aquaculture Alliance both conduct independent audits, and recognize operations which achieve compliance to set standards. Best Management Practices apply to both land-based and ocean-based sites. Adjustments can be made to BMP guidelines dependent on production species, systems used, sites and potential markets.

A first set of recommended BMPs specific to prioritised culture candidates for Bermuda are summarised in Table 15. This list is compiled from various reports, including Creswell and McNevin (2008), Leavitt (2009), Sims (2013). It is not a comprehensive list, but exemplifies practices addressing environmental concerns for Priority Level 1 species of this document.

Table 15. Summary of Best Management Practice (BMP) for issues specific to Bermuda aquaculture of prioritised (Level 1) bivalve and finfish species.

Species/Description of issue	**Hatchery BMP**	**Farm BMP**
A. Scallop /Source of stock	Broodstock import from certified aquaculture operation/Protocol for cleaning of broodstock pre-shipping/Broodstock maintained under quarantine conditions (closed system)	Transfer F1 generation and up to farm/No holding of imported broodstock in farm site
B. Scallop/Introduction of alien species (via imported broodstock)	Same as for 'A. Source of Stock'	
C. Oyster/Waste discharge		Site selection in areas of high flushing rate
D. Oyster/ Disease interaction	Selective breeding for disease control	Reduce densities for disease control
E. Oyster/Impact on benthos		Appropriate site selection-sandy/sediment/rocky bottoms
F. Finfish/Feed	Increased use of alternative sustainable food source/Improve FCR of fish	Increased use of agricultural oils and proteins (soy, canola, wheat, corn and poultry meal and oil)/ Improve FCR of fish
G. Finfish/genetic interactions with wild stock	Selective breeding to maintain wide gene pool/ Prohibit use of any broodstock beyond F2 generation	Strict protocol for maintenance of cages preventing tear and escape of juvenile and adult fish
H. Finfish/Source of stock and Introduction of alien species (via import)	Import fertilised eggs from certified hatchery	N/A
I. Finfish/Effluents	Filtration and disinfection protocols	N/A
J. Finfish/Waste discharge	Management and removal of waste	Select high current velocity sites offshore/Manipulation of diet/Integrate oyster culture downstream from the cages to absorb the nutrients released/Fallowing*
K. Finfish/use of antibiotic	Conduct therapeutant use under oversight of regulatory body/ Alternative chemical- use of Hydrogen Peroxide (approved by USDA organic agriculture standards	Removal of infected fish from cage
L. Finfish/escape	N/A	Improve net material Strict maintenance protocol to prevent holes in netting
M. Finfish/fluke infestation and disease interaction with wild stock	Routine checks. Treatment/vaccination of fish prior to transfer to farm site	Submerge cages/Reduce stocking density/Reduce Surface area:Volume ratio of cages/Weekly sampling/ Remove infected fish from cage

* Fallowing is the practice of relocating or not re-stocking marine fish cages to allow the sediment below to undergo natural recovery, both geochemically and ecologically, from the impacts of nutrient loading; this is successfully implemented worldwide (Price and Morris, 2013). Under ideal conditions, farms should not require a fallowing period for the purpose of sediment recovery.